Sveriges lantbruksuniversitet
Swedish University of Agricultural Sciences

Faculty of Landscape Architecture, Horticulture and Crop Production Science

Intercropping for enhanced yield stability and food security

Samodling för förbättrad skördestabilitet och livsmedelssäkerhet

Md. Raseduzzaman

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Foreword

As a student from an agrarian country like Bangladesh, where more than two thirds of the population is directly engaged with agriculture for their subsistence and livelihood, and where agriculture plays a significant role in country's economy, it was drawn to my attention that how could we ensure the food security of the country's vast population. Besides, as a part of agrarian family and spending most of my life in touch with farmers, I closely saw and realized that how the current conventional farming system is deteriorating our agroecosystems. I thought that it might be the only way, as I had no solution. But after starting the agroecology program I got my solution and I understood that the way we are producing food is not sustainable. This program have given me the opportunity to deeply understand the complex agricultural systems in a holistic way.

However, with my background in the field of agriculture, at the beginning of the program particularly during 'agroecology basics' course, everything seems to me new and discrete, but after some way forward I realize that everything is interconnected with each other like a spider's web. This program have rephrased my ideas and expanded my knowledge, not only in agroecosystems but also in the entire food system, and allowed me to understand that these systems not only are based on the relationship of plant, soil and water but also extends to scrutinize factors in the economic, ecological and social environments. In my whole learning process I have understood that a farm field is not only an outdoor factory where we would supply input in one end and gain a maximum output in other end, but also a cross section of many complex processes to be understood and integrated, where there are multiple goals and where the perpetual resilience is the key attribute to achieve the long term sustainability in food systems. Moreover the combination of natural science with social science, this program have provided a valuable insight to me. During my study I understand that how much important the agroecological practices are to achieve the sustainability in the current broken food production systems. Finally my thesis work on intercropping and its valuable outcome will sets out a pathway for how the agroecological approach can make an evermore significant contribution to the world's food security.

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Abstract

Current monoculture food production facing a lot of challenges. The adverse effect of climate change will shift the current agricultural production towards critical threshold level in many parts of the world. Increased global mean temperature, changes in rainfall pattern, pest and disease infestation and other localized extreme events significantly decreases the yield level and increases the yield variability year to year in current monocropping systems, throwing more than 1 billion people in food insecurity. Now-a-days intercropping have been considering as a viable alternatives for increasing the agricultural productivity and reducing the yield variability over the years. No quantitative synthesis have been made on intercropping yield stability. The aim of this study is to analyze the intercropping ability to enhance yield stability and ensure food security compare with monocropping systems. This study consists of two intertwined section: meta-analysis and field experiment. Meta-analysis on intercropping literature was conducted to quantify the yield stability of intercrops, focusing on the effect of intercrop components, experimental patterns, intercropping design and climatic zone. The three years field experiment was used to analyze the effect of three different nitrogen levels (0, 40 and 80 kg N ha^{-1}) and five different cropping systems (IC1= 80:20; IC2=50:50; IC3= 20:80 of barley & pea respectively; barley sole crop; pea sole crop) on productivity, land use efficiency and yield stability. In meta-analysis only coefficient of variation (CV) but for field experiment CV and coefficient of regression have been used for assessing the yield stability. The meta-analysis results showed that cereal-legume intercropping systems significantly reduces the yield variability of their respective sole crops. Intercropping in replacement design have significantly lowest CV value. In tropical region cereal production shows higher yield variability than intercrop and legume sole crop. However, in tropical region intercropping reduces 49% yield variability of cereal sole crops, although higher yield stability was observed in sub-tropical region for all cropping systems. Moreover the analysis showed that a higher yield level provides higher yield stability in production systems. Results of the field experiment showed that N fertilizer has no strong effect on the intercrop yield. N fertilizer significantly increases barley grain and biomass yield but reduces the pea yield. Moreover N fertilizer significantly reduces LER values indicating that available soil N decreases the complementarity among the intercrop component crops and increases the interspecific competition. No significant difference was observed among the CV of cereal sole crop and intercrops except legume sole crop. The regression analysis showed that intercropping with higher pea proportion have higher yield stability in both grain and biomass yield. Finally all of the analysis showed that cereal-legume intercropping have a substantial impact on higher yield and yield stability and could improve the food security and livelihood. Overall following this agroecological practice in cropping systems could keep contribution to move the current agroecosystems one step towards sustainability.

Key words: Meta-analysis, Intercropping, Yield stability, Food security, livelihood, Climate change, Pea-barley intercrop, Fertilizer effect.

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1. Introduction

1.1. Climate change and agriculture

Agriculture has to address simultaneously three intertwined challenges: ensuring food security for increasing global population through increased productivity and income, adaptation to climate change and mitigation of climate change without hampering the production (Beddington et al., 2012a; Beddington et al., 2012b; Foresight, 2011; FAO, 2010). The global food system not yet provide enough food and nutrition for every people of the planet. Today nearly 1 billion people, out of a world population of 7 billion, live in chronic hunger, 1.5 billion people suffering malnutrition with more 30% people in sub-Saharan Africa and more than 60% people from West Africa is being undernourished, and it is predicted that at 2050 more than 2 billion people will be suffered by food insecurity (Bruinsma, 2009; World Bank, 2007). Global population are predicted to increase to around nine billion at 2050 and with the changing the dietary habit due to rising income, a recent analysis on calories and protein consumption, it is estimated that the global food production need to be increased by 100-110 percent at 2050 (Tilman et al., 2011). Byerlee and Alex (2005), predicted that for each 10 percent increase of food production, an average 7.2 percent of income-poor people will reduce in sub-Saharan Africa. Crop production, which is vital to global food security, is being affected by climate change all over the world.

Climate change already has significant effect on agriculture and is expected further direct and indirect effects on crop production (Lobell et al, 2011). Over the next decades, the adverse effect of climate change will shift the current agricultural production towards, and perhaps over, critical threshold level in many developing regions. Increase the global mean temperature; reduced amount of total rainfall; changes in the rainfall pattern; unavailability of irrigation water; the frequency and intensity of natural disaster like hurricane, cyclone, tornedo, hailstorm etc.; rising of sea level and salinization of crop land; perturbation in ecosystems, all will have profound impact on agriculture (Beddington et al., 2012b; Thornton & Cramer, 2012; Gornall et al., 2010; IPCC, 2007a).

It is estimated that climate change already reduced global maize and wheat yield by 3.8% and 5.5% respectively. Climate change is also expected to cause substantial reduction of crop production in southern Africa (up to 30% maize production by 2030) and south Asia (up to 10% in rice production and more than 10% in other cereals like maize and millet) (Lobell et al., 2008). In mid to high latitude, due to mean temperature increase, depending on the crops, productivity may slightly increase. But researchers also concern that even in temperate climates, if the existing crop variety continue to be used, the potential yield level will be decline due to short growing season, faster crop maturation, less availability of water, proliferation of weeds and outbreak of new pests and diseases (Matthews et al., 2013). On the other hand, in low latitude, if temperature is slightly changed crop production will decrease dramatically, as the temperature in this region already reached near critical physiological threshold level for most of the crops (Battisti & Naylor, 2009; IPCC, 2007c). Localized extreme events, proliferation of weeds and sudden outbreak of pests and diseases are already causing greater unpredictability in production and instability in yield from season to season and year to year (FAO-PAR, 2011). According to the International Food Policy Research Institute (IFPRI), such climate change will cause an increase of between 8.5 to 10.3 percent malnourished children in the developing countries, compared with the scenario without climate change (Nelson et al., 2010).

In Africa, only 7 percent of agricultural land is currently under irrigation (Harmeling et al., 2007). In this region almost all producers totally dependent on rainfed agriculture and changes in any rainfall will significantly affected their livelihood. Even if the total amount of rainfall is unchanged in certain region, but due to changes in rainfall pattern, even in small amount, could have a substantial impact on food production (Harmeling et al., 2007). Such impact is very significant for the smallholders and pastoralist (IPCC, 2007a). According to the IPCC, yield in rainfed agriculture could decrease as much as 50% in large area of Africa by 2020 as the climate become hotter and drier (IPCC, 2007b). Climate change even threatening the irrigated agriculture particularly irrigation depending on underground water as the underground water table goes down faster due to possible precipitation decrease (Kang et al., 2009). Climate change also put pressure on the hydrological cycle, including the natural replenishment of surface and groundwater resources (Dracup & Vicuna, 2005). This problems has already affected the South Asia particularly Bangladesh and India, and some countries in Africa. It was predicted that agricultural outcome could decline 28% in Africa, 24% in Latin America, and 19% in Asia by 1980 (Cline, 2007). Only in India the agricultural production would decline as much as 38% and in some African countries such decline will be more than 50%. Climate change also has severe impact on biodiversity loss resulting significant extinction of beneficial species and reduction of ecosystem services that is essential crop sustainable crop production (Gonzalez, 2010).

At the same time agriculture is also responsible for global climate changes through GHG gas emission. Agriculture is directly responsible for approximately 13.5% of global GHG emissions, in the form of nitrous oxide (N_2O), methane (CH_4) and carbon-di-oxide (CO_2) (IPCC 2007b). Current monocropping agriculture is the major sources of global N_2O emission, mostly due to fertilizer application, accounting for 58% of total emission, and methane accounting for 47% of total emission, mainly coming from livestock and rice cultivation (FAO, 2013). Inefficient utilization of fertilizer also responsible for the destruction of marine, freshwater, and terrestrial ecosystems (Vitousek et al., 1997). One IPCC report estimated that if current industrial agriculture continue, it will increase 35-60% more N_2O emission by 2030 and CH_4 by 60% (IPCC, 2007b). Moreover, Changes in land use like conversion of forest lands, peat lands, savannas and grass land to crop land are responsible for additional 17.4% of GHG emissions, mainly in the form of carbon dioxide (IPCC, 2007b). In addition, manufacturing of agricultural inputs (nitrogen fertilizer and pesticides), use of fossil fuel in farm machineries, processing, packaging and transportation of food, all of these have significant contribution in total GHG emission. If all of this emissions are taken into account, then agriculture is responsible for total 32.2% of global GHG emission, making the sector single largest contributor of anthropogenic GHG emission (Gonzalez, 2010).

To address the aforementioned three intertwined challenges, food systems have to become, at the same time, more efficient and resilient, at every scale from the farm to the global level. In current situation, food production system have to contribute to mitigate climate change by efficient utilization of available resources to produce more food in a sustainable way and become more resilient with the changing climate. Climate-smart agriculture (CSA), sustainable intensification, and ecological intensification are ways forward to produce more food sustainably to enhanced food security in a changing climate (FAO, 2013). The aim of this concept is to sustainably increase agricultural productivity as well as income through adaptation with climate change and keep contribution to mitigate climate change through reducing and/or removing GHG emission relative to conventional agriculture by involving different crop management methods.

There are many different approaches and practices for sustainable crop production that can contribute to mitigate climate change. These are conservation agriculture, crop diversification, cover cropping, mulch cropping, intercropping with legume, agroforestry, judicious use of fertilizers and organic amendments, integrated nutrient management, integrated pest management, promotion of legume in crop rotation, use of nutrient-use efficient crop varieties, and water conservation etc. (FAO, 2013).

There are also many approaches and practices for successful crop production that have the ability to adapt with the climate change, including conservation agriculture, cover cropping, intercropping with legumes, mulch cropping, integrated nutrient and soil management, integrated pest and weed management, crop diversification, water harvesting, organic agriculture, and grassland management etc. (FAO, 2013). Among all of these CSA practices, intercropping is considering as a multifunctional practice, which can keep contribution in both adaptation and mitigation to climate change.

1.2. Intercrop and its advantages

Intercropping is an ancient agricultural practice, have been followed in most developing countries especially in the small scale and subsistence farming (Machado, 2009). It can be defined as the agricultural practice of growing two or more crops together in the same field in such a way that the period of overlap is longer enough including the vegetative stage (Anil et al., 1998; Ofori and Stern, 1987; Gomes and Gomez, 1983). Vandermeer (1989) defined intercrop as 'the cultivation of two or more species of crop in such a way that they interact agronomically (biologically)'. This component crops of intercrop don't necessarily have to be grown at the same time nor have to be harvested at the same time, but they should be grown together for a significant period of time of their growing period to interact each other (Lithourgidis et al., 2011). It is also referred as mixed cropping or polyculture.

Intercropping patterns generally categorized into four types: Mixed intercropping, row intercropping, strip intercropping and relay intercropping (Vandermeer, 1989). Mixed intercrop is the growing of two or more crops simultaneously in the same field without following any distinct row arrangement or grown together in the same row without any distinct sequence; row intercropping is the growing of two or more crops simultaneously where at least of the crops is planted in rows, where the other crops may be grown in rows or randomly with the first one; strip intercropping is the methods of "growing two or more crops simultaneously in different strips wide enough to permit independent cultivation but narrow enough for the crops to interact agronomically"; relay intercropping is the growing of two or more crops simultaneously during part of the life cycle of each where the second crop is planted when the first crop is at its reproductive stage but before the maturity (Mousavi & Eskandari, 2011; Vandermeer, 1989). Mixed intercropping is mostly followed by the indigenous people in slash and burn or in fellow agriculture, or when the crops are grown with the purpose of animal feed. Row intercropping and strip intercropping system much more common in modern agriculture especially where the machineries are intensively used and the harvested crops are mainly used for human consumption, also for animal feed. Among the intercropping components cereal-legume intercrop is most popular across the world.

Now-a-days self-sustaining, diversified, low-input, and energy-efficient agricultural systems like intercropping have been considered as the efficient way to achieve the sustainability in agriculture by many farmers, researchers, and policy makers worldwide (Jackson et al., 2007; Altieri, 1999). The most common advantage of intercropping is the production of higher yield in a specific area by making more efficient use of the available growth resources in a complimentary way which might not be utilized efficiently by the sole crops (Javanmard et al., 2009; Dhima et al., 2007; Banik et al., 2006). Traditional mono cropping system may be totally dependent on synthetic fertilizer and pesticides and responsible for major portion of GHG emission. Where inclusion of legumes in intercrop produce its own nitrogen from atmosphere via symbiotic N_2 fixation and supply N to the other intercrop species via vesicular arbuscular mycorrhizal hyphae or via rhizodeposition or mineralization of legume litter (Carlsson & Huss-Danell, 2014; Hauggard-Nielsen & Jensen 2005; Johansen and Jensen 1996; Frey and Schüepp, 1993) resulting in a reduction of the requirement for inorganic fertilizer application as well as mitigating GHG emission. The legume intercrop residues also provide significant amount of N to the subsequent crops (Hauggaard-Nielsen et al., 2012, Jensen et al., 2012; Karpenstein-Machan and Stuelpnagel, 2000). Moreover when fertilizer access is limited or farmers have no ability to buy nitrogen input or in organic farming where nitrogen is often considered as a limiting growth resources, then atmospheric nitrogen fixation by legume is the major sources of Nitrogen in the cereal-legume intercropping system (Naudin et al., 2010; Fujita et al., 1992).

Intercropping brings diversity of species in the cropping systems, and is considered to make the systems more resilient against environmental perturbations, thus enhancing food security (Frison et al., 2011). It provides high insurance against crop failure, especially in the extreme weather conditions like temperature stress, drought, flood, frost, pest infestation etc. and provide the farmers financial security, making the system more suitable to the subsistence farmer or labor intensive small scale farm. Intercropping is risk advantageous compare to monocrop and when one component crop of intercrop is failed, farmers still may get financial benefit by harvesting the other component crops. Intercrop also helps the farmers to maximize waster use efficiency (Yang et al., 2011), maintain soil fertility (Ilany et al., 2010), improve soil conservation, minimize soil erosion, provide resistance against lodging (Anil et al., 1998), favor weed control (Corre-Hellou et al. 2011), and reduce disease and pest incidence (Lithourgidis et al., 2011; Vasilakoglou et al., 2008), which are the serious drawback of monocropping system. Intercropping also helps the farmers to be able to cope with the seasonal price fluctuation of the crops which often destabilize their income. Moreover the small scale farmers, who don't have readily access to markets and grow enough food for themselves and their dependents, and in such cases intercrop can play a significant role to ensure their livelihood.

1.3. Yield stability in intercrop

The word stability was originated from the Latin word '*stabilis*', which means stand firm or steady (Urruty et al., 2016). It has been widely used in different scientific discipline like agriculture, social science, economics, and engineering to express the ability of an object to maintain the steadiness. The concept of ecological stability in natural science was first defined as the ability of an attribute to show consistency, regardless of any disturbance or adverse condition (Justus, 2008). However this definition for ecological stability has been expanded later to describe more ecological properties, like maintain the ecosystem function in any perturbation (Turner et al., 1993) or ability to back to initial state (Ives and Carpenter, 2007).

In agriculture, the stability concept has been mainly used to measure the spatial or temporal variability of a specific properties of the agricultural system. The term yield stability is a common term in plant breeding program and mostly used by the plant breeders to measure the superiority, adaptability and yield variability of a genotype over a wide range of environmental condition. Yield stability have two different concept; static concept of yield stability and dynamic concept of yield stability (Becker and Leon, 1988). In static yield stability the genotype shows stable performance regardless any changes of the environmental condition. Unlike the static concept, where genotype shows constant performance, the dynamic concept permits a predictable response to the environments. In each environmental condition, the static genotype corresponds completely to the estimated level or prediction. Beaker (1981) used this concept to measure the agronomic yield stability and also this concept is widely used to measure the intercropping yield stability. In agronomy it is refers to the ability of a crop to perform consistently, whether at high or low yield level, across a wide range of environments, locations and time (Annicchiarico, 2002; Tollenaar and Lee, 2002).

Now-a-days stability in yield is been considering as an important attribute for food security. One of the important reason for food insecurity in the developing countries is the instability of yield in the current monocropping system due to its less resilient ability against environmental perturbations (Lithourgidis et al., 2011). For subsistence and small scale farmers, such stability is very crucial because of variation of environmental condition from season to season and year to year leads to the variation in annual yields and throw the farmers to the food insecurity (Trenbath, 1999). Hence, intercrop is more popular in developing world and the main reason is that it may be more stable than the monocropping systems – which often are highly dependent on external inputs, such as fertilizer and pesticides (Sileshi et al., 2012; Dapaah et al., 2003; Horwith, 1985). Numerous researchers cover the theory and mechanisms of yield stability in intercropping. Willey (1979) explicitly mentioned that intercrop provides higher yield in a given piece of land and maintain the greater yield stability in different growing seasons compare to the monocrop. Rao et al. (1981) and Dapaah et al. (2003) studied the stability of yield on both sole crops and intercrops of different species at different climatic conditions. Their results showed that intercropping were more productive and stability of yield in all intercropping systems were higher than the sole crops. One of the long term experiment of Rao and Willey (1980) on sorghum and pigeon pea intercropping reported that sole pigeon pea would fail one year in five, sole sorghum one year in eight but their intercropping system would fail only once in thirty six years.

One of the important mechanism of improved yield stability in intercropping is that, if one crop fails, or grow poorly, the other component crop of intercrop can compensate the loss; such compensation might not possible if the crops grown separately as sole crop. Another mechanism is that intercropping provides a buffer against pests and diseases (Rao and Willey, 1980). For example one component crops may act as a barrier for other component crop to spread the pests or diseases. Sometimes one component crops alters the microclimate of other crops which might not favorable for pests and diseases infestation. Even exudate release from the roots of component crops might inhibit the weed growth. Yield stability may also occur due to complementarity over competition among the component crops, which might not be possible in low input sole cropping system.

1.4. Relation between agroecology and intercrop

Current industrial agriculture like large scale monocropping, inefficient use of inorganic fertilizer and pesticides makes the current food system unsustainable in all three scale (Altieri, 2009). Agroecology - the application ecological principals to agricultural systems - is increasingly recognized as the way forward for sustainable agriculture. It is an alternative to the destructive practices and unhealthy food produced by industrial agriculture.

Wezel et al. (2009) considered the agroecology as ‘a science, a movement, and a practice’. Among the different branches of agroecology, agronomic agroecology is now more extensively practiced in different developing world (Buttel, 2003). These practices have to become more sustainable, more environmentally friendly, less input dependent, and less technology dependent than those of industrial agriculture. Where Francis et al. (2003) define agroecology as ‘as the ecology of entire food system, encompassing ecological, economic and social dimensions’. This ecology should be more resemble to natural ecology. This is because the sustainable agroecosystems would only be achieved, when agroecosystems will be more similar to the natural ecosystem in structurally and functionally (Gliessman, 2000). Agroecology mainly follow the ecological theory to design and manage the agricultural systems that are more productive than the conventional system but also resource conserving (Altieri, 1995). It is concerned with the maintenance of a productive agriculture that sustains yields and optimizes the utilization of local resources with significantly reduces the negative impact on environment and socio-economic condition. Gliessman (1998) define agroecology more clearly as 'the application of ecological concepts and principles to the design and management of sustainable agroecosystems'. These principles are: promote diversity of crops, less dependency on external and synthetic inputs, soil conservation, less GHG emission from the system, complementarity among the component of the agroecosystems etc. (Gliessman, 2007).

Intercropping, considering as an important agroecological practice, have the ability to maintain the agroecological principals and to bring the sustainability in agriculture in all scale (Gliessman, 2015; FAO, 2013; Altieri, 2009). The most important function of intercropping is that it increases horizontal, vertical, structural and functional diversity in the agroecosystems at the same time (Altieri, 2000; Vandermeer, 1989). Legume in the intercropping system reduces the requirement for external and synthetic inputs resulting low GHG emission, enhances complementarity among the component crops, brings the temporal stability in the system, and overall demonstrates many of the principles of agroecology at the autecology level. It have the ability to provide a diversity of ecological and social benefits for resource-limited farmers (Gliessman, 2015), and helps to achieve the sustainability in food system.

2. Aims and research question

The aims of this study are: 1) to perform a meta-analysis on published literatures to quantify the yield stability in intercropping compare to their respective monocropping, considering climatic condition, timescale and locations, 2) to determine the yield, land use efficiency of pea-barley intercrop, and yield stability in pea-barley intercrop and sole crop from a three years field experiment in Denmark, and 3) to discuss the potential of intercropping in enhancing food security and improve livelihood.

The overall research question of this study is: does intercropping enhance yield stability and food security? The above research question is divided into following sub-questions: 1) which kind of intercropping components have higher yield stability? 2) Does N fertilizer have effect on yield stability? 3) Does N fertilizer have influential effect on yield of cereal-legume intercropping systems?

3. Materials and methods

3.1. Meta-analysis

3.1.1. Definition of meta-analysis

In most general term meta-analysis is the one kind of research synthesis. Research synthesis can explain as the review of primary research on the given topic with the purpose of integrating the findings (Koricheva et al., 2013). However meta-analysis is not merely the form of narrative reviews but also the quantitative research synthesis to estimate the magnitude of the effects across studies. It is first developed in the medicine and various social sciences (Hedges & Olkin, 1985; Glass et al., 1981) and during 90s it was introduced in ecology and evolutionary biology (Arnqvist and Wooster, 1995; Järvinen, 1991). It is a very useful tool because this analysis is the cumulative result of the independent studies whether the effect size of a treatment is large, moderate, small or not significantly different from zero (Gurevitch et al., 1992).

The term meta-analysis was first defined by Glass (1976) as "the statistical analysis of a large collection of analysis results from individual studies for the purpose of integrating the findings". This definition means broad sense and covered almost all quantitative synthesis. Koricheva et al. (2013) defined meta-analysis more narrowly, as 'a set of statistical methods for combining the magnitudes of outcomes (effect sizes) across different datasets addressing the same research question'. It is the quantitative summary of research domains, and it refers to a specific set of statistical quantitative methods that are designed to compare and synthesize the results of multiple studies (Arnqvist and Wooster, 1995). It is a very powerful method since it is allows a highly improved control of type II statistical error where the effect size are very low and/or the sample size within the studies are very restricted. Even if the effect size and number of studies is modest in meta-analysis, type II error is drastically reduced (Arnqvist and Wooster, 1995). For example, the overall effect size may be statistically significant in meta-analysis of different studies, even if none of the single studies shows significant result.

3.1.2. Data collection from published article

An extensive peer reviewed literature search was conducted in Web of Science™ all databases on 5th January 2016, and Scopus on 11th January 2016. The initial search term was 'intercrop' OR 'mixed crop' in the title and then the literatures were subsequently refined by 'Grain yield'. The articles were sorted on relevance with the search term to get the more relevant article at the beginning. The search yielded 2,513 publications in Web of Science™ all databases and 586 publications in Scopus. An additional literature search was also conducted in Google Scholar with the search term 'intercrop' OR 'mixed crop' AND 'grain yield' in 'anywhere in the article' option, sorted them by relevance, and first 1,000 articles were considered for further action. All these yielded publications were screening carefully one by one to achieve the maximum number of articles. Total 33 articles had been accumulated (table 1) that met the selection criteria. I avoided the duplicate publication yielded in different database and also didn't include the duplicate data, for example, same experimental data or measurements reported in different publication. Meta-analysis assumes independence of data being analyzed. For example, including the multiple results from the single study or similar dataset from same experiment in different publication may alter the outcome of the data analysis and significance level, and increase the probability of type I error (Arnqvist and Wooter, 1995).

Based on the number of experiment within an article or different treatments within the same experiment, multiple datasets were extracted from each article. Here an experiment was defined by two sole crop species and their intercrop. Treatments were defined by fertilizer level, plant density, irrigation frequency, sowing dates, and intercrop pattern (mixed, row or strip intercrop) within an experiment. These 33 articles produce 54 experiments for cereal-legume intercrop, 9 experiments for non-cereal-legume intercrop, 49 experiments in temporal variability (experiment in different years), 19 experiments in spatial variability (experiments in different locations), 19 experiments in additive design, 50 experiments in replacement design, 11 experiments carried out in tropical zone, 18 experiments in sub-tropical zone, and 35 experiments in temperate zone.

To select an article for meta-analysis the following criteria had been carefully considered. This is because if the selection criteria not carefully considered, it may exclude compelling studies or alternatively include comprehensive sets of studies that only tangentially address a hypothesis (Lortie and Callaway, 2006). The experiments on annual intercropping were only considered during article selection. The experiments have to be conducted for minimum three years (temporal variability) or minimum three locations (spatial variability) or two years at two locations. The locations should be situated within the same agro-climatic zone or in the same region, if the article containing experiment conducted at different locations. Same experiment at different agro-climatic zone or region may have massive yield differences are not expectable for this analysis as in reality farmers grown their crops in the same location or different location within the same region. Articles should contained grain yield data in tabular form rather than the graphical form, as the yield data were only extracted from the tables to maintain the accuracy of the data. Article containing the mean value of grain yield for different times or location were not considered for meta-analysis, unless it contains the mean value with standard deviation (SD) for yield in the tabular form. If the article contain coefficient of variation (CV) for grain yield without mentioning data for all experimental years or locations were also extracted for analysis. Experiment containing different cultivar of same species at different locations or years was excluded from analysis; this is because different cultivars have different yield performance and may bring wrong result for yield stability.

The articles covered a wide range of agroecological condition in tropical, subtropical and temperate climatic regions and even I tried to cover all continents. The intercropping literature was dominated by the studies on cereal-legume intercrop. Although cereal-legume intercrop experiments were recorded from all climatic conditions but data from cereal-cereal intercrop were only available from China. A large proportion (76 percent) of the studies was carried out in the research station, while the rest were carried out in the farmers' field. Most of the experiments (85 percent) were laid out as randomized complete block design and the rest as split-plot design.

Table 1: List of intercropping articles used for meta-analysis

Article No.	References	Country	Year	Intercrop components	Intercrop design	Intercrop arrangements
1	Arlauskienė et al. (2011)	Lithuania	2007-2010	Cereal-legume	replacement	Both temporal and spatial
2	Xia et al. (2013)	China	2009-2011	Cereal-legume	replacement	temporal
3	Dolijanović et al. (2013)	Serbia	2003-2005	Cereal-legume	additive	temporal
4	Kadžiulienė et al. (2011)	Lithuania	2007-2009	Cereal-legume	replacement	temporal
5	Oljaca et al. (2000)	Serbia	1994-1996	Cereal-legume	replacement	temporal
6	Oseni & Aliyu (2010)	Nigeria	---	Cereal-legume	replacement	Spatial
7	Stoltz & Nadeau (2014)	Sweden	2010-2011	Cereal-legume	additive	Spatial
8	Wang et al. (2015)	China	2012-2014	Cereal-cereal	Replacement	temporal
9	Ofori et al. (1987)	Australia	1982-1985	Cereal-legume	Additive	temporal
10	Jensen (2006)	Denmark, France, Germany, Italy, UK	2003-2005	Cereal-legume	Additive & replacement	temporal
11	Abera & Feyisa (2010)	Ehiopia	1997-1999	Legume-legume	replacement	temporal
12	Qin et al. (2013)	China	2009-2011	Cereal-legume Cereal-cereal	replacement	temporal
13	Jensen (1996)	Denmark	1980-1982, 1984	Cereal-legume	replacement	temporal
14	Zhang et al. (2007)	China	2001-2004	Cereal-cotton	replacement	temporal
15	Šarūnaitė et al. (2010)	Lithuania	2007-2009	Cereal-legume	replacement	temporal
16	Corre-Hellou et al. (2006)	France	2001-2003	Cereal-legume	replacement	temporal
17	Zhang et al. (2011)	China	2007-2009	Cereal-legume	replacement	temporal
18	Workayehu & Wortmann (2011)	Ehiopia	1996-2000	Cereal-legume	replacement	temporal
19	Reddy et al. (1992)	Niger	1986-1988	Cereal-legume	additive	temporal

20	Ahmed and Rao (1982)	China, India, Philippines, Sri lanka, Thailand, USA, Australia	1976-1979	Cereal-legume	additive	spatial
21	Mu et al. (2013)	China	2008-2010	Cereal-cereal	Additive	temporal
22	Subedi (1998)	Nepal	2008-2010	Cereal-legume	Additive	Spatial
23	Andrade et al. (2012)	Argentina	2007-2009	Legume-sunflower	Replacement	Temporal
24	Arlauskienė et al. (2014)	Lithuania	2007-2009	Cereal-legume	Replacement	Spatial
25	Naudin et al. (2010)	France	2007-2008	Cereal-legume	Replacement	Spatial
26	Ong et al. (1991)	India	1985-1987	Cereal-legume	Replacement	Temporal
27	Dolijanović et al. (2009)	Serbia	2003-2005	Cereal-legume	Additive	Temporal
28	Chimonyo et al. (2016)	South Africa	2013-2015	Cereal-legume Cereal-bottle gourd	Additive	Temporal
29	Yang et al. (2011)	China	2006-2008	Cereal-cereal	Replacement	Temporal
30	Szumigalski & Acker (2005)	Canada	2001-2003	Cereal-legume-oilseed	Replacement	Spatial
31	Dapaah et al. (2003)	Ghana	1997-1999	Cereal-legume - root crop	Replacement	Spatial
32	Mohta & De (1980)	India	1970-1974	Cereal-legume	Additive	temporal
33	Rao & Willey (1980)	India	1972-1978	Cereal-legume	Additive	Both temporal and spatial
34	Ngwira et al. (2012)	Malawi	2008-2011	Cereal-legume	Additive	temporal
35	Midega et al. (2014)	Kenya	2005-2012	Cereal-legume	Additive	temporal
36	Waddington et al. (2007)	Zimbabwe	1993-2006	Cereal-legume	Replacement	temporal
37	Akinnifesi et al. (2006)	Malawi	1992-2002	Cereal-legume	Replacement	temporal

In meta-analysis phenomenon of publication bias is well known (Koricheva et al., 2013) and generally this bias happed when the published studies tend to report larger or more significant effect sizes (e.g. effect of a treatment). Sometimes these publication bias results from the biased sample of effect size in the literature may affect the meta-analysis result if the same datasets are used for same analysis. However here I hypothesized that if any publication bias may occur, it has no impact on this meta-analysis result due to the different interest of use of dataset. Almost all intercrop articles used grain yield data to compare the effectiveness of the treatments as well as to compare the yield performance between sole crops and intercrops, but here the grain yield data have been used to measure the coefficient of variation (CV) to analyze the yield stability. During the literature extraction from the database there was no biased for experimental location, journal title and publication year. The intercrop component species were also independent during literature extraction. But the experiments must have the sole crop treatment for both intercrop component species to compare the yield stability between sole crop and intercrop. However during data extraction, besides aforementioned 33 articles, I got 4 more articles (articles 34-37 in table 1) containing 15 experiments reported only the cereal sole crop and cereal-legume intercrop data. Those datasets were also extracted, and analyzed separately.

Due to the lack enough dataset for non-cereal-legume intercrop combination (for example cereal-cereal, legume-legume, cereal-oilseed crop etc.) further investigation of yield stability in experimental pattern, intercrop design and climatic condition were not performed.

3.1.3. Response variable

In all analysis, Coefficient of Variation (%CV) was taken as the response variables. Coefficient of variation is widely used to quantify and compare year to year yield stability or variability of crops, and Higher CV value indicating the lower yield stability and vice versa (Smith et al., 2007; Rao & Willey 1980). %CV was defined as:

$$\%\mathrm{CV} = \frac{\mathrm{S}}{\overline{\mathrm{X}}} \times 100$$

Where S and $\overline{\mathrm{X}}$ are the standard deviation and mean value of the grain yield in sole crop or intercrop at different year or location within an experiment.

Treatments of different external inputs such as level of N fertilization, irrigation frequency and pesticides level may be different in intercrop than from sole crop. In those cases, only the treatments of same N and pesticide level, and same irrigation frequency in intercrop as sole crop were considered to calculate CV. In the statistical analysis, for more than one treatment in the cropping systems with in the same experiment, the mean value of CV of all treatments have been used. For example, if the experiment contained three treatments of different densities of component crops in intercropping system, then the mean value of CV of all three treatments have been used for analysis, rather than considering CV values separately.

3.1.4. Explanatory variables

In the meta-analysis, four explanatory variables have been used, i.e. (1) intercrop component, (2) experimental pattern, (3) Intercrop design, and (4) climatic zone. Among the intercrop components cereal with legume are the dominant combination among the experiments. Hereafter I categorize the intercrop components into two groups, cereal-legume intercrop and non-cereal-legume intercrop. The experimental pattern categorize into two level, stability over years (temporal variability) and stability over locations (spatial variability). Stability over years was defined as the stability within the experiments carried out for three or more years in the same location, where stability over locations was defined as the stability within the experiments carried out at three or more location in the same year. Moreover experiments carried out for two years at two or more different location also considered for spatial variability. Mostly intercropping have been designed as additive design or replacement design. Additive design was defined as at least one component species of intercrop have the equal density as sole crop, where in replacement design density of one sole crop species have been proportionally replaced by other crop in the intercrop (Vandermeer, 1989). In the additive design, the intraspecific interactions are held constantly at a fixed density, even as interspecific interactions are added in intercrop. But in the replacement design, the interspecific interactions in intercrop are replaced with the potentially reduced intraspecific interaction (Iverson et al., 2014). Hence the total competition is lower in replacement design than the additive design. Here I want to observe the effect of intercrop competition on yield stability in both additive and replacement design.

In the analysis the experiments have been categorized into tropical zone, subtropical zone and temperate zone. Experiments carried out between 0-23°50' north and south latitude were considered for tropical zone; experiments between 23°50'- 45°0' north and south latitude were considered for subtropical zone; and rest other experiments considered for temperate zone. Values of all variables were extracted directly from the article.

3.1.5. Statistical analysis

Special analytical methods are needed when the response variables are not expected to be identically distributed i.e. the variance of the observations among the studies are assumed to be unequal (Hedges et al., 1999). The studies extracted for meta-analysis were carried out at different climatic condition and different location. Moreover different experiments contained different species and cultivar in the cropping systems. Even for the same species yield performance and yield stability was different in different experiment. Due to such unspecified distribution, data was analyzed by nonparametric method with Friedman test. Nonparametric yield stability measures are distribution-free and are not affected by outliners as parametric estimates (Nassar, & Huehn, 1987). This techniques are ideal for use when the response variables are used on nominal (categorical) and ordinal (ranked) scale rather than on measured value. This is also useful when the response variable don’t meet the stringent assumptions of the parametric techniques (Field, 2013). The whole statistical analysis were performed by using Minitab 17 statistical software.

During analysis with Friedman test, at the beginning data were analyzed for all three cropping systems together (cereal sole crop, legume sole crop, and cereal legume intercrop; or sole crop 1, sole crop 2 and intercrop) for all explanatory variables. If the interaction among three cropping systems is significant at $P<0.05$, then I compared two cropping systems with each other separately for all explanatory variables. During analysis CV values were used as response, cropping systems as treatment, and experiments as block. Instead of mean value, Friedman test calculate the median value of CV to analyze the significance of differences. This significance of median value is analyzed on the basis of sum of ranks for each cropping system rather than median value itself.

Besides Friedman test, a data analysis was also performed by manually ranking the CV of the cropping patterns of each experiment. The highest CV (lowest yield stability for that cropping system) in the experiment received 3 point and the lowest CV (highest yield stability) received 1 point, where the intermediate one received 2 points. Then the analysis of variance (ANOVA) of the cropping systems based on ranking value was performed by using general linear model. Then the significance of differences between the mean values (rank) of cropping systems were estimated using t-test at $P<0.05$. The significance of differences of cropping systems was same for both Friedman test and t-test statistical procedure.

3.2. Field experiment

Information related to field experiment and all dataset were extracted from Jensen et al. (1985), a national report in Danish.

3.2.1. Experimental site

The field experiment was carried out for three cropping seasons from 1980-1982 at the Risø National Laboratory (55°41' N, 12°05' E), Roskilde, Denmark. The soil was sandy loam soil (Typic Hapludalf) consists of with 11% clay, 14% silt, 49% fine sand and 25% coarse sand representative for the eastern part of Denmark. In the top 20 cm soil the initial inorganic N content ($NO_3^- + NH_4^+$) was 1.61, 0.87 and 1.26 mmol N kg^{-1} soil in 1980, 1981 and 1982 respectively. During the study the soil pH (water) was 6.8, 6.3 and 7.6 in 1980, 1981 and 1982 respectively. Every year the preceding crop was white mustard (*Sinapis alba* L.) and during the autumn season each year it received 30 kg P ha^{-1} and 50 kg K ha^{-1}. The 25-years mean annual rainfall at Risø is 550 mm, mean annual air temperature 8°C with maximum and minimum air temperature of 16°C (July) and -1°C (February). During the cropping season total rainfall from 1st April to 18th August was 204 mm, 242 mm, and 220 mm in 1980, 1981, and 1982 respectively. In 1982, during the growing season the distribution of rainfall was optimal for vegetative growth, grain filling and ripening.

3.2.2. Experimental design and crop management

The experiment consisted of two sole crops and three different intercrop pattern of spring barley (*Hordeum vulgare* L. cv. Nery) and field pea (*Pisum sativum* L., cv. Bodil). The intercrop pattern was followed proportional replacement design by replacing 20, 50 and 80 percent of barley sole crop (BSC) plant population with corresponding percentage of pea sole crop (PSC) population: 80 percent barley with 20 percent pea (IC1), 50 percent barley with 50 percent pea (IC2) and 20 percent barley with 80 percent pea (IC3). The plant population in the sole crop was 300 plant m^{-2}

for barley and 80 plant m^{-2} for pea. All cropping systems were treated with three N fertilization levels: 0, 40 and 80 kg N ha^{-1} (0N, 40N and 80N) applied as calcium nitrate ($Ca(NO_3)_2$). The fertilizer was broadcasted two weeks after seed sowing.

The experiments were laid out in a split-plot design with three replication in which N fertilization levels as main plots, and pea, barley sole crop and intercrop pattern as subplots. The main plots were arranged as randomized block design and subplots were arranged within each main plot. Each subplot consisted of ten rows with a length of 3.2 m each and row to row distance was 14 cm. For both sole crop and intercrop, seeds were sown by a ten-rowed sowing machine at 16, 13 and 7 April, and crops were harvested at 8, 14 and 3 August in 1980, 1981 and 1982 respectively. Pea plant started flowering during mid-June and barley started flowering one week later. The crops were harvested at complete maturity stage (approx. 16 weeks after sowing). No mechanical weeding was performed during growing season. During the middle of May weedicide (bentazon) was applied to control weeds, insecticide (paranthion) was applied to control leaf eating weevil (*Sitona lineatus*) and aphids, and triadimefon was applied to control barley mildew (*Erysiphe graminis*). In 1981 barley sole crop was attacked by barley net blotch (*drechslera teres*). In 1980 and 1981 lodging of plants were observed with the increasing pea population in intercrop and with the increasing N fertilization. No lodging was observed in 1982 except in pea sole crop.

3.2.3. Plant sampling and analytical methods

Crops were harvested for sampling at complete maturity stage. The middle six rows (2.2 m^2) were cut by hand just above the soil surface. After intercrop harvesting pea and barley plants were separated by hand and initial weight were taken for each component. Then the samples were dried for 20 hours at 80°C temperature to measure the samples dry matter content. Grain yield and biomass yield is reported as g m^{-2}.

The advantage of intercrop compare to sole crop was determined by using Land Equivalent Ratio (LER). It is one of the common way of measuring yield advantages of intercrops over sole crops. LER is defined as the relative land area under sole crop that is required to produce the same yield achieved in the intercrop (Rao & Willey 1980; Vandermeer 1989). LER for the pea-barley intercrop was calculated on the basis of grin dry matter yield in both sole crop and intercrop, as the sum of partial LER value for barley (L_B) and pea (L_P) in accordance with the De wit and Van den Bergh (1965):

$$L_B = \frac{Y_{B-IC}}{Y_{B-SC}}$$

$$L_P = \frac{Y_{P-IC}}{Y_{P-SC}}$$

$$LER = L_B + L_P$$

Where Y_{B-IC} and Y_{P-IC} are the grain dry matter yield of barley and pea components in intercrop respectively, and Y_{B-SC} and Y_{P-SC} are the grain dry matter yield of barley and pea in sole crop respectively. LER values greater than 1 indicates the intercrop advantage over sole crop in terms of improved utilization of natural resources for plant growth. When LER value is less than 1, it indicates resources are more efficiently utilizes in sole crop than intercrop.

Besides the CV analysis, the yield stability was also analyzed by calculating the coefficient of regression for all cropping systems. When the variable (yield) are normally distributed, coefficient of regression is an effective method to measure the yield stability of a cropping system in different environment (Grover et al., 2009; Raun et al., 1993). This technique is widely used in plant breeding program to measure the stability of a genotype in changing environment (Calderini & Slafer, 1998; Becker & Leon 1988). Now-a-days researchers also used this techniques to assess the yield stability in the intercropping system (Grover et al., 2009; Blade et al., 1992; Rao & Willey, 1980). In the regression stability analysis, environmental index was calculated as the annual mean yield (grain and biomass yield calculated separately) of all cropping systems within same N fertilization level. Environments are then ranked by yield level to produce a quantitative gradient of environmental productivity irrespective of the cause of variability in yield (Hildebrand, 1984). Lower the value of environmental index indicating poor environmental condition and higher value indicating good environmental condition for crop production. Then the yield of individual cropping pattern are regressed on the environmental index and then the regression line are compared between sole crops and intercrop, and among the intercrop patterns. The cropping pattern which show lower regression coefficient have higher yield stability.

3.2.4. Statistical analysis

All the measured variables were assumed to be normally distributed and the analysis of variance (ANOVA) of grain yield, biomass yield, LER, Coefficient of variation (CV) were performed by using general linear model in Minitab 17 statistical software. The least significant difference among the treatments was measured by Fisher's test with P value at .05 level if the main effect or interaction was significant. The coefficient of regression for yield stability was also analyzed by using Minitab 17 statistical software.

4. Results

4.1. Meta-analysis

4.1.1. Effect of intercrop component on yield stability

Among the intercropping system cereal-legume intercrop is the dominant combination across the globe. Among the experiments extracted from the articles, 86% of the experiments were on cereal-legume intercrop. The stability of yield is highly desirable to the producers. Intercrop components have substantial impact on yield stability. Among the cereal-legume intercropping experiments, in 43% of the experiments, intercropping showed higher yield stability than its respective cereal and legume sole crop, and intercropping in 46% of the experiments showed intermediate yield stability compared to both sole crops. In most of the experiments, among three cropping systems, legume sole crop showed the poorest yield stability performance. In the statistical analysis, yield stability in cereal-legume intercropping system is significantly higher ($P \leq 0.001$) than the legume sole cropping system (Fig. 1). Also cereal-legume intercropping have remarkably higher stability than cereal sole crop. Even in non-cereal-legume intercropping system, intercropping showed higher stability than their respective sole crops (fig. 2).

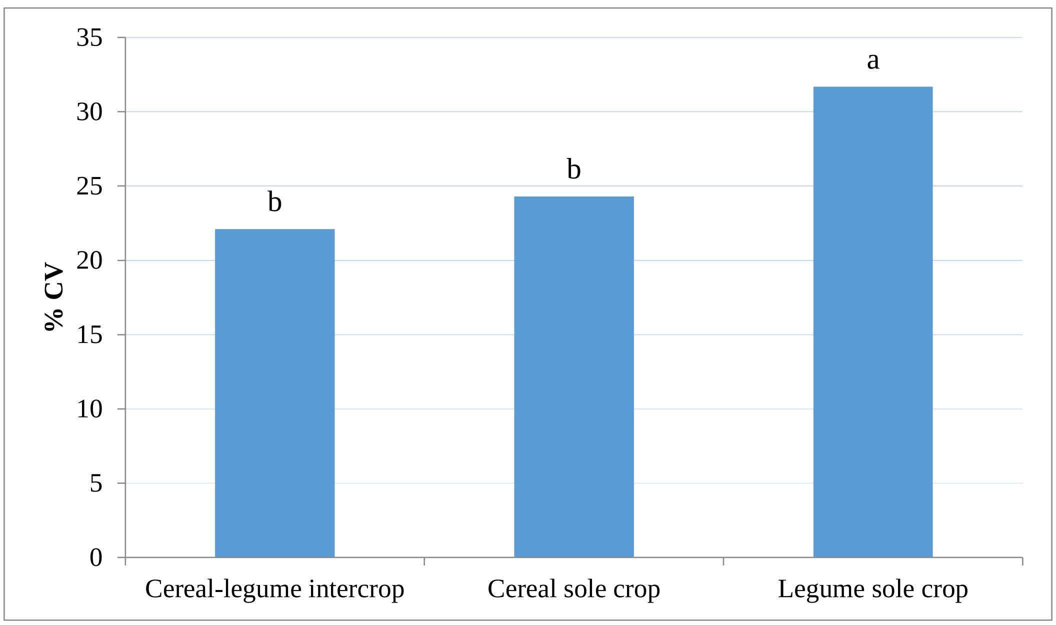

Fig. 1: Coefficient of variation (%CV) in cereal-legume sole crops and intercrop. Values are the median (n=54). Different letters above the bar indicating the significant difference among the CV values.

Between the cereal-legume and non-cereal-legume intercropping system, the cereal-legume intercrop showed 10% and 45% (percentage of %CV difference) more yield stability than its respective cereal and legume sole crop, is higher than the non-cereal-legume intercrop, where former one showed 9% and 29% more than its respective sole crops.

The analysis of the 15 experiments containing only cereal sole crop and intercrop dataset also showed the magnitude of the stability difference between sole crop and intercrop (fig. 3). Intercropping in 100% experiments gave higher yield stability than its respective cereal sole crop. Also in the statistical analysis the difference of CV between intercrop (15.8) and cereal sole crop (27.2) is highly significant (P<0.001) and indicated that yield in intercrop is 72% more stable than the cereal sole crop.

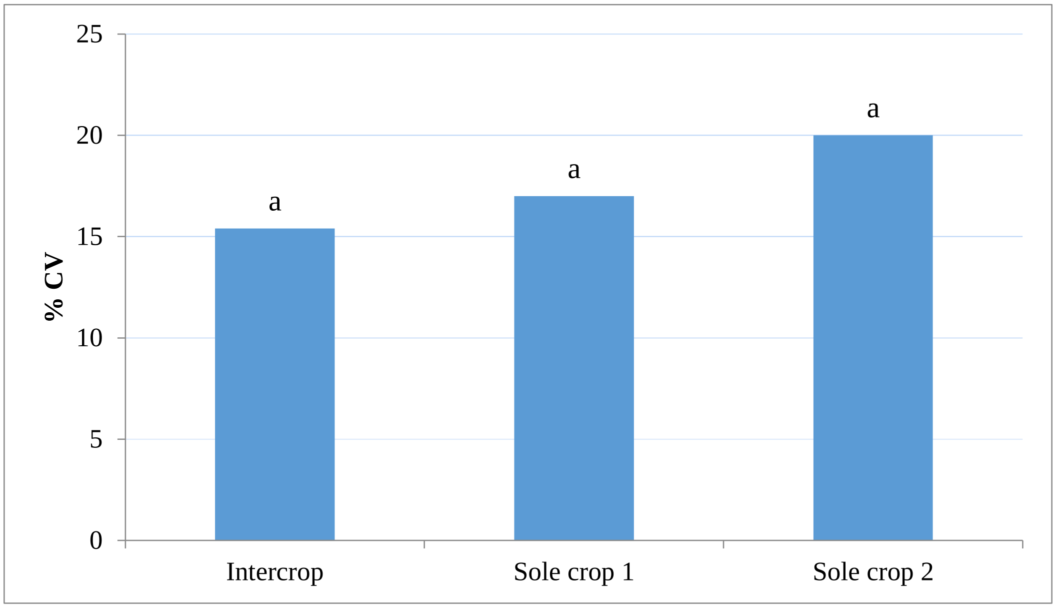

Fig. 2: Coefficient of variation (%CV) in non-cereal-legume intercrop and their respective sole crops. Values are the median (n=9). Different letters above the bar indicating the significant difference among the CV values.

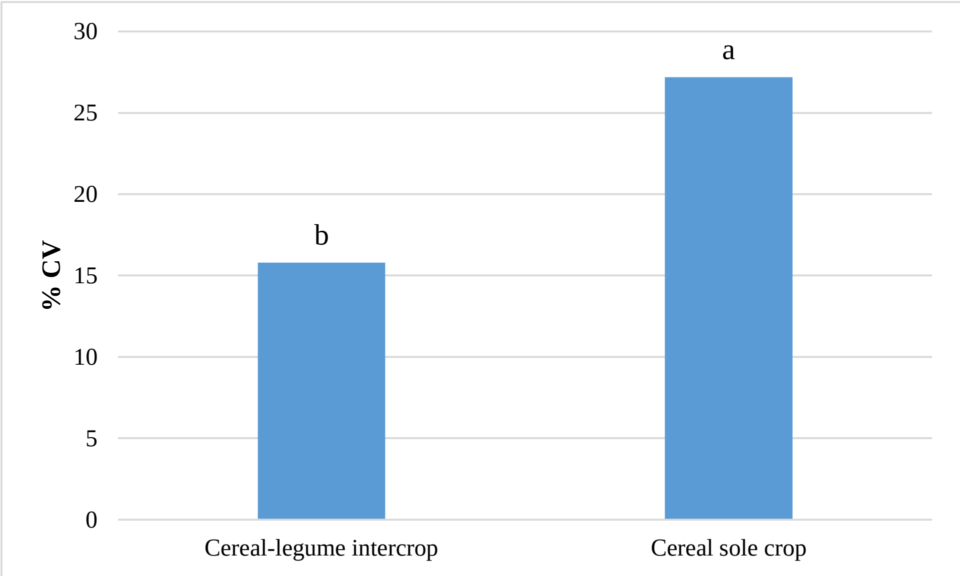

Fig. 3: Coefficient of variation (%CV) in cereal-legume intercrop and cereal sole crop. Values are the median (n=15). Different letters above the bar indicating the significant difference among the CV values.

In the regression analysis it was observed that there is a significant negative correlation between grain yield level and CV for all cropping system (fig. 4). With the increasing grain yield level the CV values were decreased. In cereal sole crop, the CV value was decreased 1.37 unit with the increase of per unit grain yield ($P<0.05$) and in legume sole crop it was decreased 5.28 unit ($P<0.001$). But in Intercrop the slope (1.32) was less steep than the both cereal and legume sole crop ($P=0.05$). The lower coefficient value in intercrop (1.32) compare to both sole crops indicated that in any yield level intercrop have the ability to give more stable yield than the sole crops. This relationship also indicate that the use of the high yielding cultivar in the cropping system may have the ability to increase the yield stability than the low yielding cultivar.

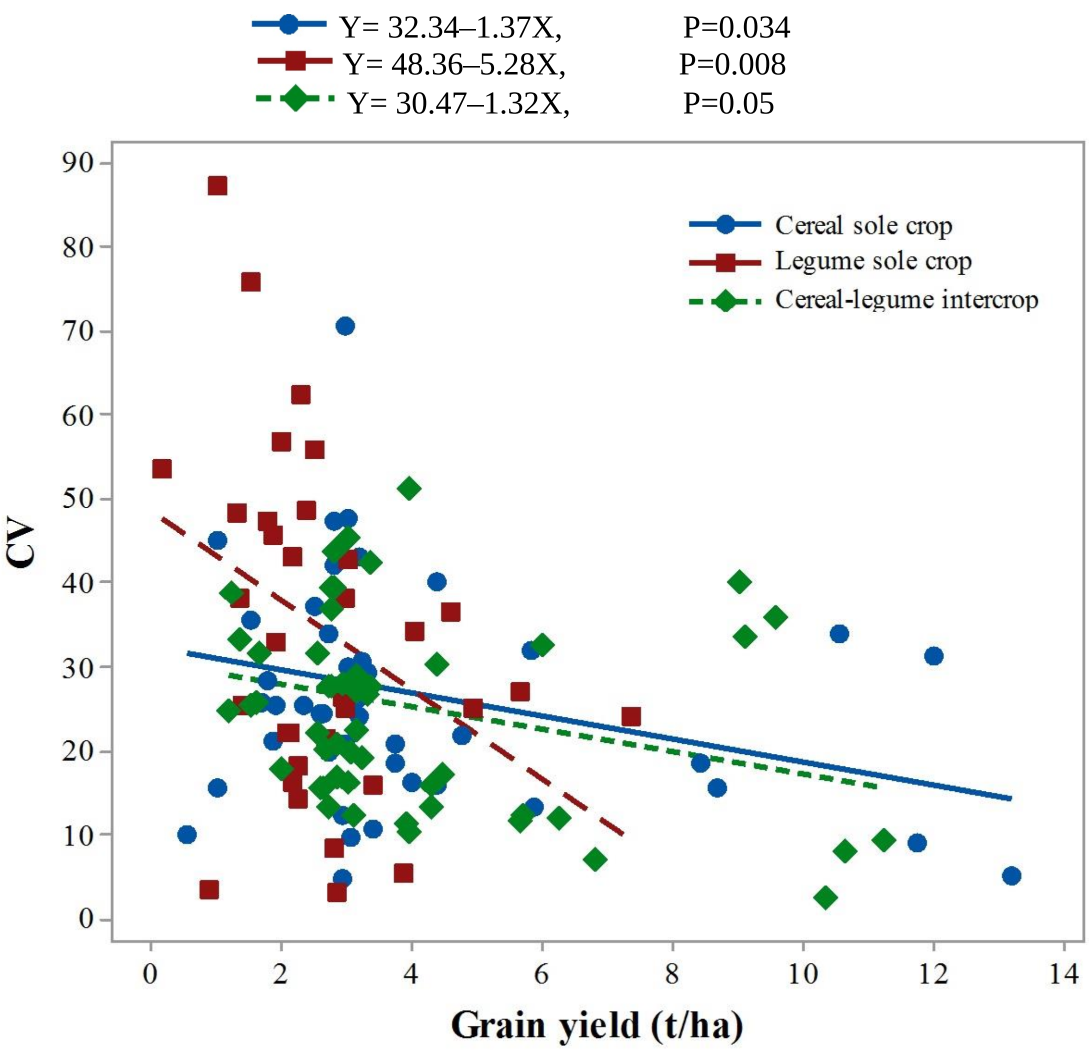

Fig. 4: Correlation between grain yield level and %CV for cereal-legume sole crops and intercrop. The correlation shows a tendency for CV to decrease as grain yield level increase. Each data point is the mean value of grain yield in each experiment. P values are related to the slopes of the regression.

4.1.2. Yield stability in different experimental pattern

Experiments used in meta-analysis, most of them (72%) were carried out in temporal variability (over a number of experimental years). Experiment in temporal variability is the common practice to the researchers. Also in reality yield stability in same ecological niche for a specific crops in different years is highly desirable to the farmers. However in this analysis I tried to quantify the yield stability for both temporal and spatial variation. To perform the analysis only cereal-legume experiments were analyzed for both experimental pattern.

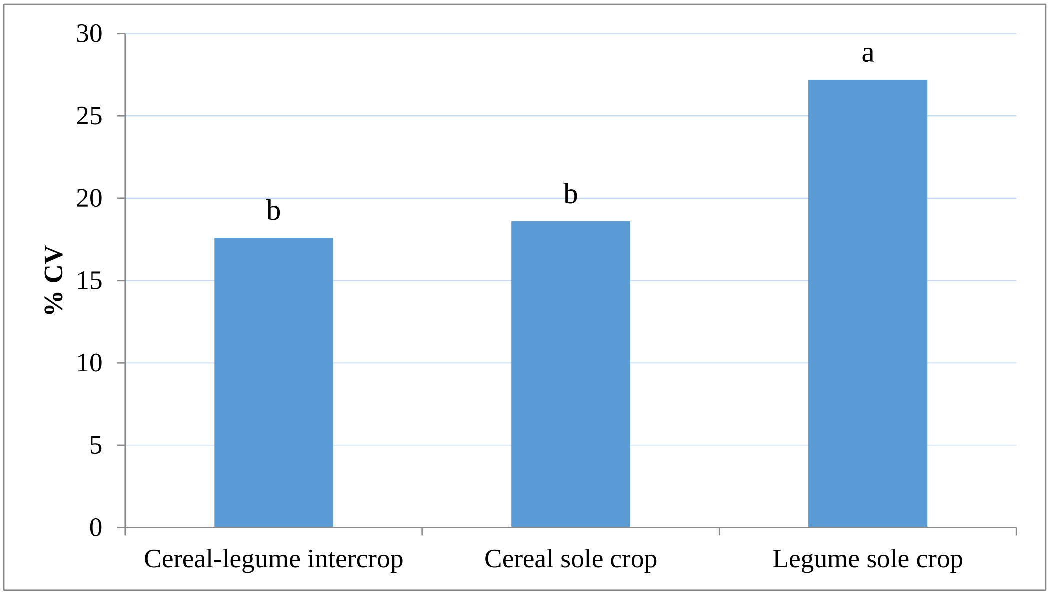

Fig. 5: Coefficient of variation (%CV) in cereal-legume sole crops and intercrop in temporal variability. Values are the median (n=49). Different letters above the bar indicating the significant difference among the CV values.

In temporal variability, CV of cereal-legume intercropping was 6% and 58% (percentage of %CV difference) less than cereal and legume sole crop respectively and the difference between intercropping and legume sole crop was highly significant ($P<0.01$) (Fig. 5). In spatial variability, yield stability in intercropping system was significantly higher ($P<0.05$) than both sole cropping system and the CV was 14% and 19% lower than cereal and legume sole crop respectively (Fig. 6). Although compare to temporal variability, in spatial variability intercropping system showed significantly higher yield stability than the cereal sole crop, but all the cropping system in spatial variability showed higher yield fluctuation (higher CV value) than the same cropping system in temporal variability. Comparing between two experimental pattern, in temporal variability, intercrop, cereal sole crop and legume sole crop showed 85%, 100% and 42% more yield stability respectively than the same cropping system in spatial variability.

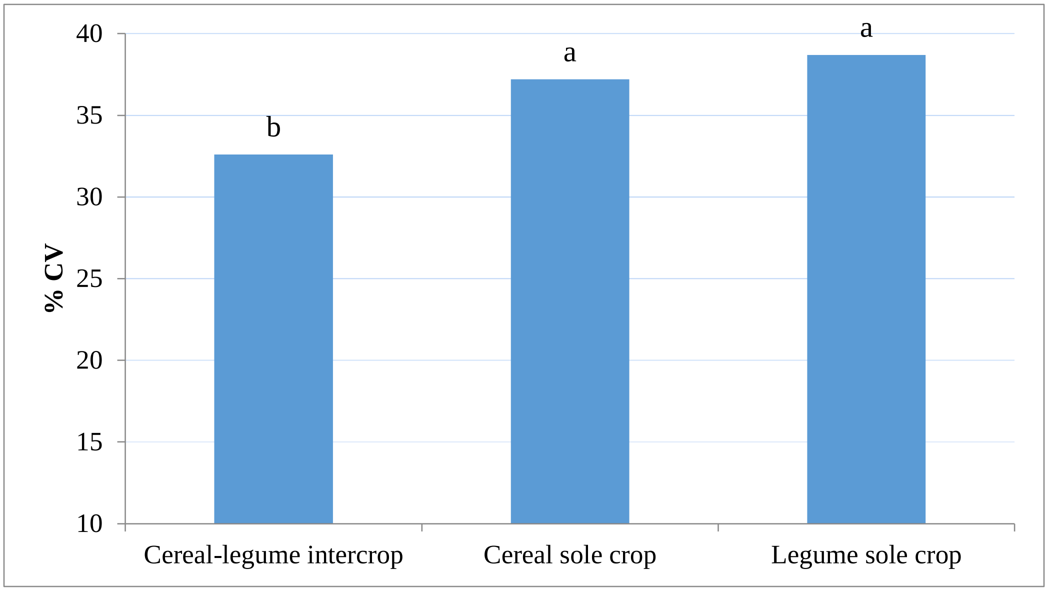

Fig. 6: Coefficient of variation (%CV) in cereal-legume sole crops and intercrop in spatial variability. Values are the median (n=19). Different letters above the bar indicating the significant difference among the CV values.

4.1.3. Effect of intercrop design on yield stability

Plant density in intercrop is an important factor for stability in yield. In more extent, yield stability in intercrop depends on the efficient utilization of environmental resources and complementarity among the intercropping components, which is significantly influenced by relative density total (RDT) in intercrop. Both additive and replacement design are widely used in intercrop, however, in this analysis a large number of experiments (72%) followed replacement design and only 28% experiment in additive design.

In the analysis replacement design has significant positive effect on yield stability than the additive design. In the additive design, yield stability in intercropping is lower than the cereal sole crop. But compare to the legume sole crop, CV is 39% lower in the intercrop (Fig. 7).

By contrast, intercrop in the replacement design (Fig. 8) showed significantly higher yield stability than both cereal sole crop ($P<0.05$) and legume sole crop ($P<0.001$). In replacement design, CV in intercrop was 32% and 59% lower than the cereal and legume sole crop respectively. Moreover, in replacement design, CV in intercropping is 14% less than the intercropping CV in additive design, makes the replacement design more efficient for intercropping yield stability.

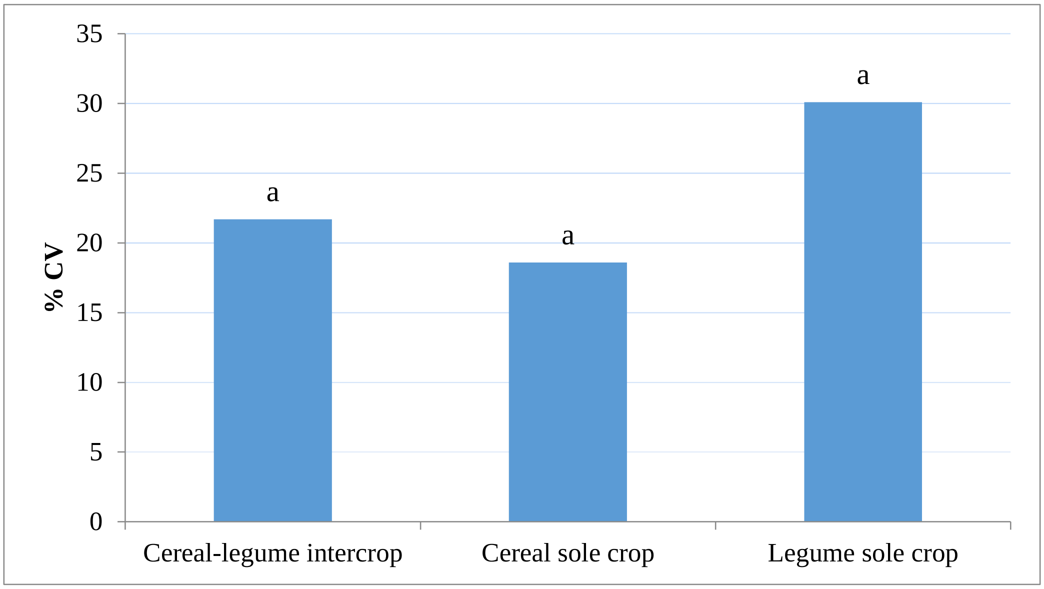

Fig. 7: Coefficient of variation (%CV) in cereal-legume sole crops and intercrop in additive design. Values are the median (n=19). Different letters above the bar indicating the significant difference among the CV values.

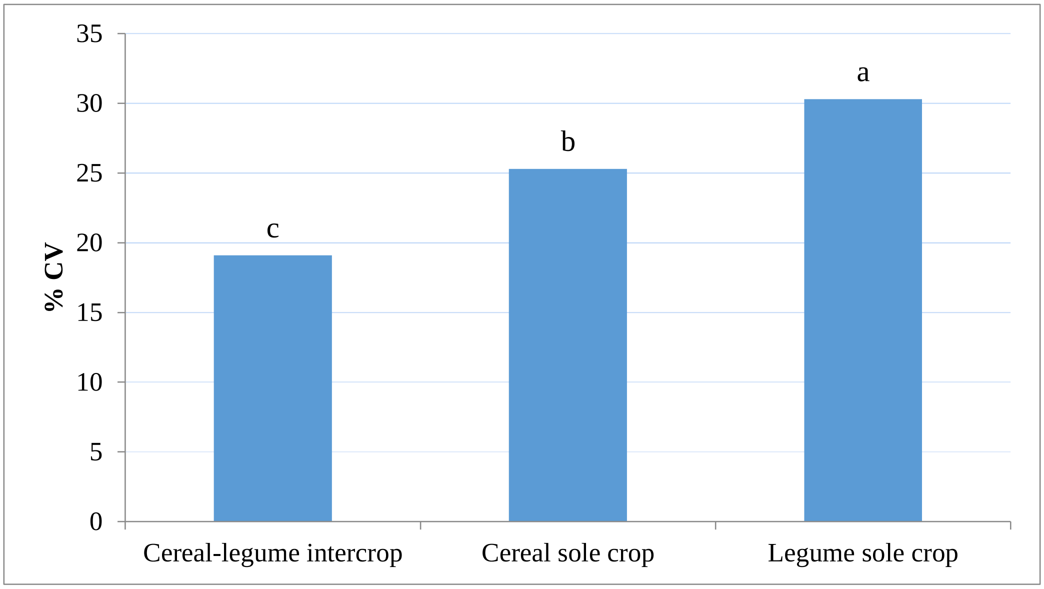

Fig. 8: Coefficient of variation (%CV) in cereal-legume sole crops and intercrop in replacement design. Values are the median (n=50). Different letters above the bar indicating the significant difference among the CV values.

4.1.4. Impact of climatic zone on yield stability

The analysis showed that climatic conditions have significant influence on yield stability of cropping systems. However for this analysis I didn't find sufficient amount of long term experiments on intercropping in tropical climate compared to subtropical and temperate climate. Most of the long term intercropping experiments were carried out in temperate climate. Among the analyzed experiments, only 17% experiments were from tropical climate, 28% from sub-tropical climate and rest 55% experiments from temperate climate.

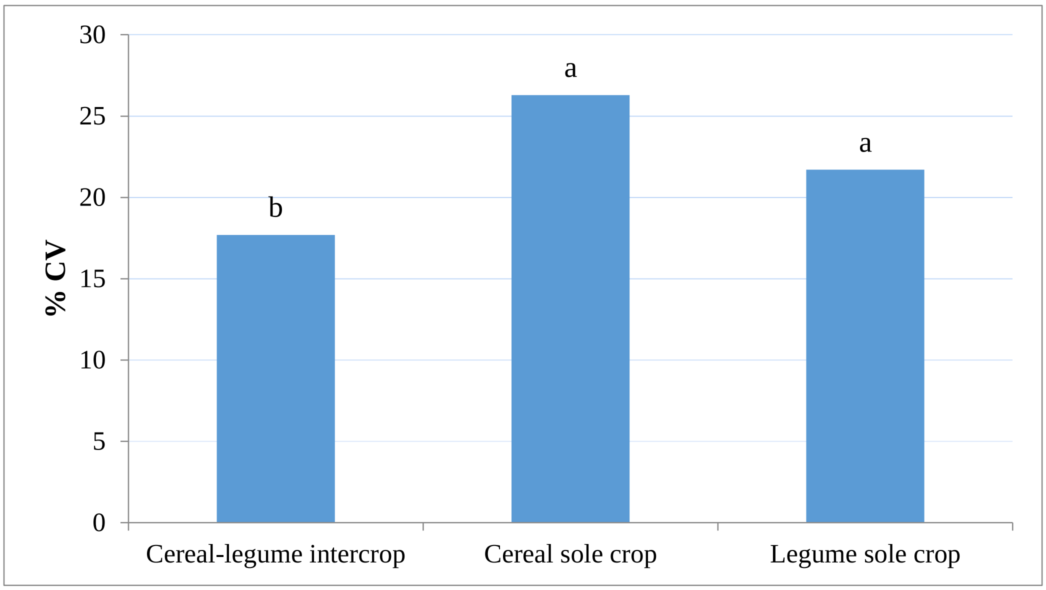

Fig. 9: Coefficient of variation (%CV) in cereal-legume sole crops and intercrop in tropical zone. Values are the median (n=11). Different letters above the bar indicating the significant difference among the CV values.

The analysis result reveals that different climatic conditions, particularly temperature variation, alter the stability behavior of the cropping systems. If one cropping system showed better yield stability performance in one climatic condition, it showed different stability behavior in another condition. In the analysis this was particularly happened with cereal sole crop. In tropical zone, especially in the countries lies in low latitude where the climate is changing alarmingly and vulnerable for crop production, cereal crop production showed lowest yield stability among all three climatic zones (Fig. 9). Even in tropical zone, stability in cereal sole crop was lower than legume sole cropping system. However in all climatic conditions, cereal-legume intercropping system showed highest yield stability than their respective sole crops. In tropical climate, stability in intercropping was significantly higher ($P<0.05$) than both sole crops. In intercropping CV was 49% less than cereal sole crop and 23% less than legume sole crop. No significant difference of CV was observed between cereal and legume sole crop.

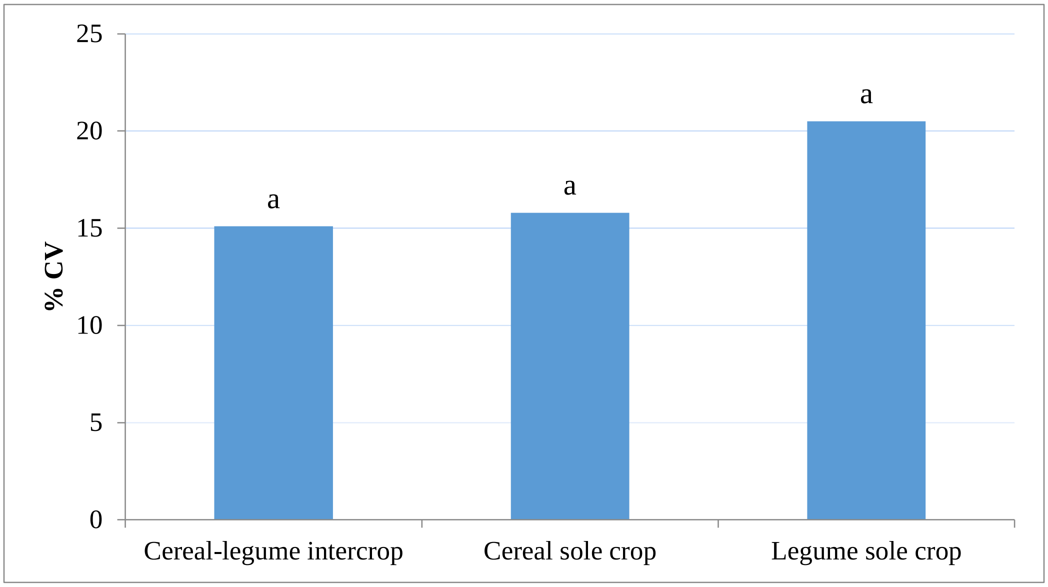

Fig. 10: Coefficient of variation (%CV) in cereal-legume sole crops and intercrop in sub-tropical zone. Values are the median (n=18). Different letters above the bar indicating the significant difference among the CV values.

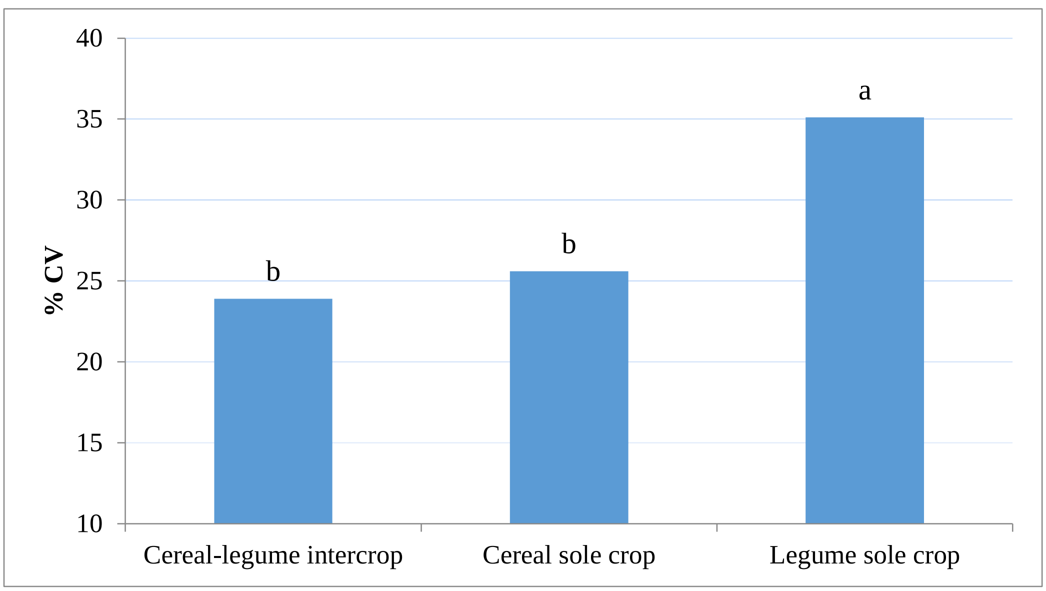

Fig. 11: Coefficient of variation (%CV) in cereal-legume sole crops and intercrop in temperate zone. Values are the median (n=35). Different letters above the bar indicating the significant difference among the CV values.

In subtropical zone, no significant difference was observed among the cropping systems (Fig. 10). However, here intercropping have highest yield stability and the CV is 5% and 36% lower than cereal and legume sole crop respectively. Contrary to tropical climate, in temperate climate, legume sole crop showed very poor stability performance and was significantly lower ($P<0.001$) than both cereal sole crop and cereal legume intercrop (Fig. 11). No significance difference was observed between intercrop and cereal sole crop, although, CV in intercropping was 7% lower than cereal sole crop. I observe a tendency of increasing stability gap between legume sole crop and intercrop with the increasing the latitude. In tropical climate where the stability gap was 23%, in subtropical climate it is 36% and in temperate climate it is 47%. Moreover, surprisingly all cropping systems in subtropical zone showed lowest CV among all climatic zones indicating that intermediate temperature is favorable to achieve the higher yield stability in crop production system.

4.2. Field experiment

4.2.1. Environmental effect on grain and biomass yield

Analysis of variance for grain and biomass yield indicated the interaction between growing seasons and treatments. Different environmental conditions among the different growing seasons significantly affected the grain yield.

In 1981, due to net blotch attack in barley, both grain and biomass yield in barley was lower than the other growing seasons (Table 4). But in total yield of pea and barley for both grain and biomass, this decrement was compensated by the pea-barley intercrop, as pea yield was positively affected by the subsequent growing seasons. Such compensation in the intercropping system maintain the stability in the yield despite the different environmental conditions in different growing seasons.

Moreover lodging of crops affected both grain and biomass yield in 1980 and 1981. Conversely, in 1982, due to absence of lodging and uniform distribution of rainfall over the whole growing season, grain yield was significantly higher ($P<0.05$) than preceding two growing seasons. No significant difference was observed among the growing seasons for total biomass yield. However in 1982, total biomass yield was higher than previous cropping seasons.

4.2.2. Grain and Biomass yield

The analysis of variance indicated a significant interaction among the cropping systems, and N level in grain and biomass yield. In biomass yield, significant difference ($P<0.05$) was observed between sole crop and intercrops (table 2). In zero nitrogen treatment, intercrops gave higher biomass yield than both sole crops. This yield difference was reduced with increasing level of nitrogen fertilizer due to the increasing tendency of barley biomass yield in sole crops and reducing tendency of pea biomass yield in intercrop. Hence in 80 kg nitrogen level pea biomass was significantly lower ($P<0.05$) than both barley sole crop and intercrops. No significant difference was observed among the cropping systems in grain yield. However in all nitrogen level, higher average grain yield was observed in most of the intercropping systems than their respective sole crops.

The experiment results showed a contrasting behavior in grain and biomass yield between barley and pea with the increasing level of N fertilizer. Results showed a significant difference among different N level for grain and biomass yield (table 3). With the increasing N level, barley grain yield was significantly ($P<0.05$) increased. Compare to zero nitrogen level, in 80 kg N level, 45% more barley grain yield was observed. Contrary to the barley grain yield, pea grain yield was decreased with the increasing N level but no significant difference was observed for total grain yield among the nitrogen level. Similar to the grain yield, biomass yield also showed significant difference among the N level. With the increasing N fertilizer barley gave significantly higher ($P<0.05$) biomass yield (table 3). Conversely, like grain yield, pea biomass yield also showed the reduced tendency with the increased N fertilizer level, indicating that N fertilizer have negative impact on legume yield.

Table 2: Grain yield (g m^{-2}), Biomass yield (g m^{-2}) and LER for grain yield as affected by main effect of N fertilization level and sub-plot effect of cropping system in 1980, 1981 and 1982.

Cropping system	N level (kg ha^{-1})	Total grain yield (g m^{-2})				Total biomass yield (g m^{-2})				LER			
		1980	1981	1982	Mean	1980	1981	1982	Mean	1980	1981	1982	Mean
BSC	0	404	386	393	394 a	711	686	685	694 b				
IC1	0	416	461	453	443 a	771	842	779	797 ab	1,17	1,16	1,07	1,13 a
IC2	0	479	551	514	515 a	843	973	890	902 ab	1,52	1,33	1,16	1,34 a
IC3	0	495	547	549	530 a	923	1034	940	966 a	1,83	1,28	1,14	1,42 a
PSC	0	199	445	639	428 a	524	542	988	685 b				
BSC	40	546	503	522	524 a	996	988	972	985 ab				
IC1	40	554	532	537	541 a	1075	1046	1002	1041 ab	1,05	1,07	1,02	1,05 a
IC2	40	555	550	543	549 a	1228	1092	1033	1118 a	1,11	1,12	1,01	1,08 a
IC3	40	538	531	566	545 a	1062	1057	1026	1048 ab	1,21	1,1	1,01	1,11 a
PSC	40	351	467	634	484 a	732	896	1093	907 b				
BSC	80	578	517	541	545 a	1149	1098	1095	1114 a				
IC1	80	546	486	606	546 a	1195	1081	1197	1158 a	0,98	0,96	1,12	1,02 a
IC2	80	553	517	576	549 a	1169	1111	1147	1142 a	1,05	1,05	1,05	1,05 a
IC3	80	537	500	577	538 a	1145	1053	1104	1101 a	1,18	1,08	1,02	1,09 a
PSC	80	330	400	636	455 a	711	999	1005	905 b				

Note: BSC: barley sole crop; IC1: barley 80% and pea 20%; IC2: barley 50% and pea 50%; IC3: barley 20% and pea 80%; PSC: pea sole crop. For Grain yield and biomass yield, values in each year are the average of three replication. Mean values followed by different letters within the same N level indicating significance difference at $P<0.05$.

Table 3: Cumulative effect of different N level on pea and barley grain and biomass yield (g m^{-2}).

N level (kg ha^{-1})	Grain yield (g m^{-2})			Biomass yield (g m^{-2})		
	Barley	Pea	Total	Barley	Pea	Total
0	328 b	250 a	462 a	610 c	426 a	809 b
40	441 a	220 a	528 a	888 b	378 a	1020 a
80	474 a	184 a	526 a	1008 a	329 a	1084 a

Note: In each column different letters for values indicating significant difference at P<0.05. Values are the mean (n=12 for both barley and pea yield; n=15 for total yield).

On the other hand, among the intercropping systems, I observed a tendency of increasing total grain and biomass yield with the increasing of pea proportion in intercrop in all growing seasons and this tendency was particularly confirmed in 0 and 40 kg N level.

In this study it was also observed that, barley showed a high degree of plasticity in terms of grain and biomass yield in intercrop when the sowing density of barley in intercropping systems was reduced by 20, 50 and 80 percent across all N level. With the reducing 20, 50 and 80 percent sowing density in intercrop, yield level was only reduced by 6, 15 and 39 percent in grain yield, and 2, 8 and 31 percent in biomass yield respectively, across all fertilization level. However such plasticity was not observed in pea crop.

Table 4: Effect of different growing seasons on grain yield (g m^{-2}), biomass yield (g m^{-2}), and LER for grain yield.

Year	Grain yield (g m^{-2})			Biomass yield (g m^{-2})			LER
	Barley	Pea	Total	Barley	Pea	Total	
1980	428 a	162 a	472 b	876 a	310 a	949 a	1.23 a
1981	374 a	243 a	493 b	781 a	434 a	967 a	1.13 ab
1982	441 a	250 a	552 a	848 a	389 a	997 a	1.07 b

Note: In each column different letters for values indicating significant difference at P<0.05. Values are the mean (n=12 for both barley and pea yield; n=15 for total yield; n=9 for LER).

4.2.3. Land-use efficiency of intercrop

LER for intercrop grain yield indicating the efficiency of growth resources utilization by intercropping relative to the sole cropping, and advantage from intercropping. The analysis showed the interaction among the cropping system, N level and growing seasons for LER. LER values for different intercropping systems are shown in table 2.

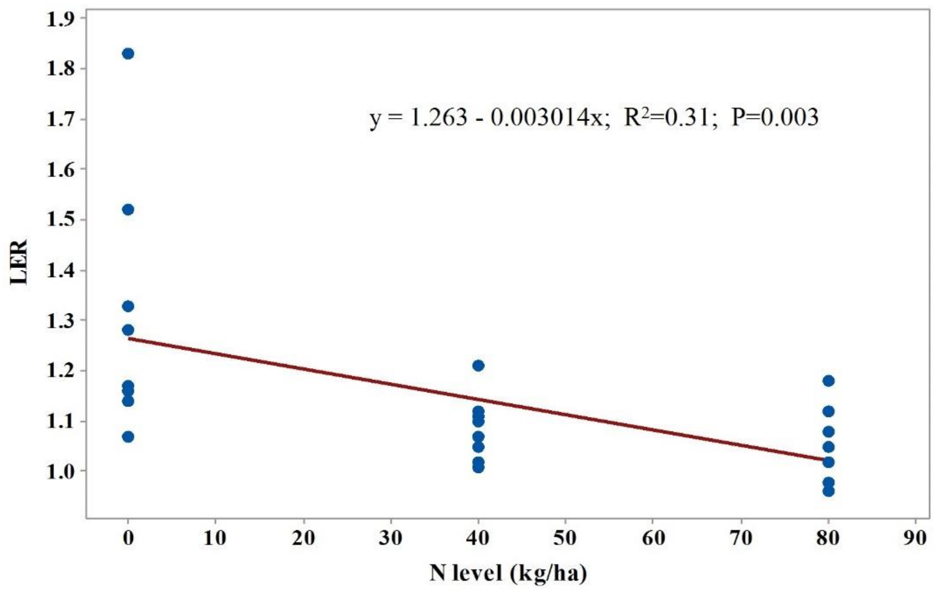

Fig. 12: Correlation between LER and N fertilization level (kg ha−1) for pea-barley intercropping system. The correlation shows a tendency for LER to decrease as N level increase. P values are related to the slope of the regression.

LER results showed that the environmental resources were utilized up to 83 percent more efficiently in intercrop than their respective sole crops. All of the intercropping systems showed the LER values more than 1, except IC1 cropping system in 80 kg N level in 1980 and 1981 growing seasons, indicating the lower intraspecific and interspecific competition with higher complementarity among the component crops in intercrop. Pea plant showed a positive effect on LER and was observed that LER value increase with increasing the pea plant proportion in the intercrop across all N level, although no significant difference was observed among the cropping system. Moreover I also observed a tendency of decreasing the LER with the increasing the nitrogen level and this was confirmed by the significant regression ($P<0.01$) between LER and nitrogen level as illustrated in fig. 12. The growing season also have significant effect ($P<0.05$) on LER (table 4). LER values was decreased on average over the growing seasons (from 1.23 in 1980 to 1.07 in 1982) and this indicates that a higher degree of complementarity in the use of growth resources was occurred in 1980 growing season.

Considering the barley and pea crops separately, partial LER of barley (0.80) was significantly higher ($P<0.001$) than the partial LER of pea (0.35) and this suggests that in intercrop barley crop was strongly dominated over the pea crop. Partial LER of barley was remain almost unchanged over the three growing seasons, where the partial LER of pea was significantly decreased ($P<0.05$) from 1980 to 1982 (from 0.45 to 0.19), indicating that environmental condition was significantly affected the pea grain yield in intercrop.

Table 5: Coefficient of variation (%CV) in grain yield and biomass yield of different cropping systems

Cropping system	CV of grain yield	CV of biomass yield
BSC	4.02 b	2.03 b
IC1	6.18 b	4.71 b
IC2	4.50 b	6.27 b
IC3	5.44 b	4.08 b
PSC	38.73 a	25.6 a

Note: BSC: barley sole crop; IC1: barley 80% and pea 20%; IC2: barley 50% and pea 50%; IC3: barley 20% and pea 80%; PSC: pea sole crop. The values are the mean (n=3) of different N level. In each column different letters for CV values indicating significant difference at $P<0.05$.

4.2.4. Yield stability in sole crops and intercrops

In this study I analyze the yield stability for both grain and biomass yield separately, although to the farmers, grain yield stability is more important. Analysis of variance for grain yield CV and biomass yield CV showed a significant interaction between cropping system and growing condition (table 5). When averaged across three nitrogen level, CV of pea sole crop was significantly higher ($P<0.05$) than rest of the cropping systems for both grain and biomass yield. CV of all intercrops and barley sole crop are comparable with each other. However in both grain and biomass yield, barley sole crop have slightly lower CV than all other intercrops. Yield stability of intercropping systems showed mixed behavior in grain and biomass yield. In grain yield, IC2 cropping system showed better yield stability than other intercropping system, but in biomass yield, IC3 cropping system showed better performance in yield stability.

However estimation of yield stability by calculating the CV of either grain or biomass yield has limitation that such calculation is only based on same environmental condition (like same N level), since the individual crop response among the difference growing conditions were ignored. As a result the exact variability of yield among different condition not to be obtained. It would probably be better to calculate the yield stability considering all growing conditions to gain a precise estimation of variability. The coefficient of regression for grain and biomass yield against environmental index were plotted in fig. 13 and fig. 14 separately. In this study the regression stability analysis for both grain and biomass yield revealed that the response of the cropping systems to different growing condition was different.

BSC, y= 91.5+0.78X, $r^2=0.321$
IC1, y= 26.5+0.95X, $r^2=0.716$
IC2, y= 314.5+0.44X, $r^2=0.644$
IC3, y= 316.2+0.43X, $r^2=0.738$
PSC, y= -748.7+2.38X, $r^2=0.658$

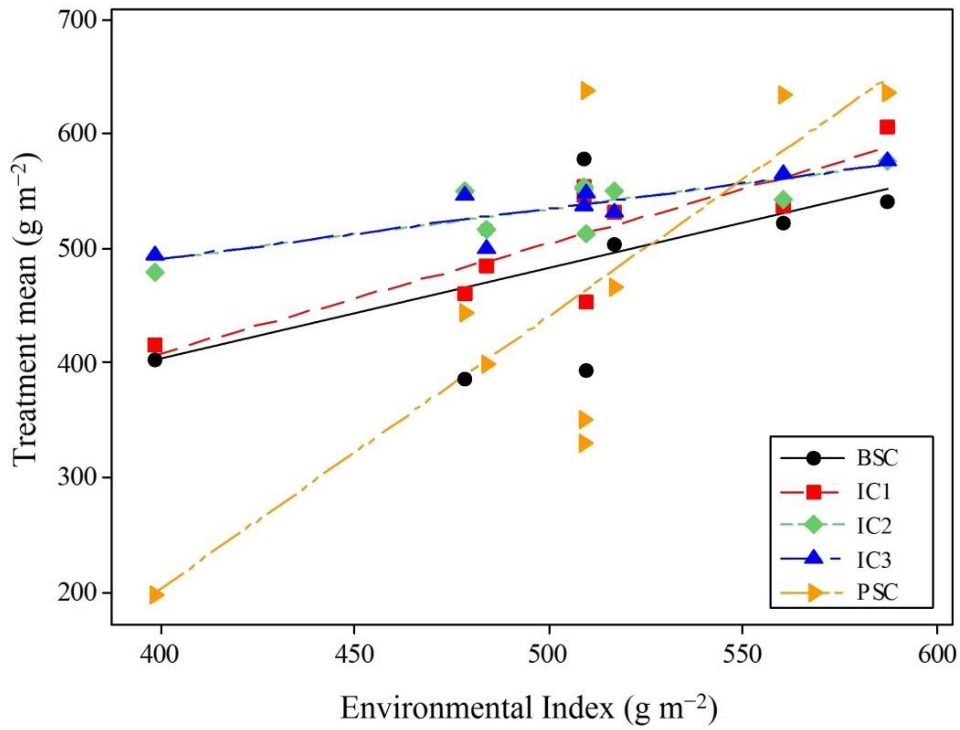

Figure 123: Linear regression of cropping system grain yield on environmental index across three N level from 1980-1982. BSC: barley sole crop; IC1: barley 80% and pea 20%; IC2: barley 50% and pea 50%; IC3: barley 20% and pea 80%; PSC: pea sole crop. Individual data point are the mean value (n=3).

The regression stability analysis showed that pea sole crop was more responsive to the environmental change because their grain yield were highly influenced by the changes in environment (b=2.38) (fig. 13). The same trend was also observed in the pea biomass yield (Fig. 14). For barley grain yield, although the slope of the regression line was lower (b=0.78) than pea sole crop and IC1 intercrop (b=0.96) but the goodness of fit of the regression line was much lower (r^2=0.32) than the all other cropping systems indicating that barley sole crop response for grain yield was very unpredictable to the environmental change. In contrast to grain yield, the slope for barley biomass yield was quite high than other cropping systems because its yield was highly affected by the environmental change (fig. 14). It also mean that the yield is quite good when the environment is favorable but the problem is if any environmental perturbations occur the yield is drastically drop down which is not desirable to the farmers.

BSC, y= -430+1.40x, r^2=0.92
IC1, y= -193+1.23x, r^2=0.91
IC2, y= 191+0.89x, r^2=0.76
IC3, y= 595+0.46x, r^2=0.68
PSC, y= -163+1.03x, r^2=0.38

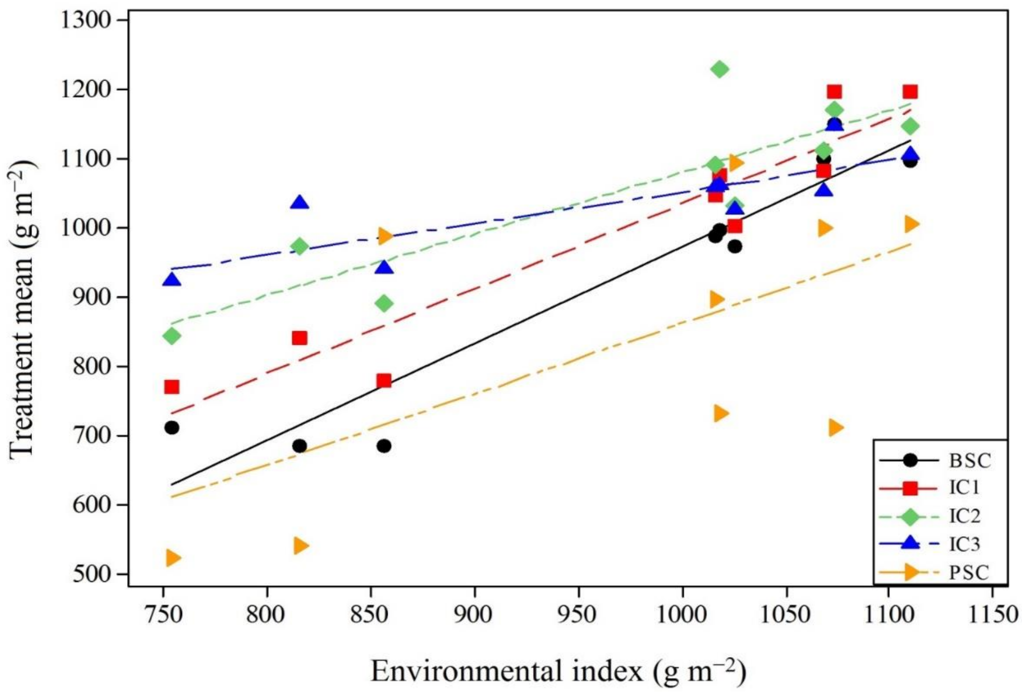

Figure 14: Linear regression of cropping system biomass yield on environmental index across three N level from 1980-1982. BSC: barley sole crop; IC1: barley 80% and pea 20%; IC2: barley 50% and pea 50%; IC3: barley 20% and pea 80%; PSC: pea sole crop. Individual data point are the mean value (n=3).

In both regression analysis, IC1 cropping system showed intermediate yield stability compared to sole crops. But in both analysis, IC2 and IC3 cropping system showed higher yield stability as their regression line was much less steep than the sole crops, because intercrop yields were less affected by the changes in the environment. Even if I compare the goodness of fit of regression line, the response of intercrops grain yields to environmental change were much more stable than the sole crops. In the analysis it was observed that, with the increasing the pea proportion in the intercrop the slope was decreased, indicating that higher proportion of pea in the intercropping have a positive effect on yield stability, despite its more variability in the sole cropping system. All the regression line in both grain and biomass yield was statistically significant ($P<0.01$) against the environmental index except barley sole crop in grain yield and pea sole crop in biomass yield. All the regression lines for intercropping system were above of both sole crops, indicating the occurrence of yield advantage of intercrop in all changing environment. However in both regression analysis, all the regression lines for intercrop and barley sole crop line were close to each other than pea sole crop due to the higher grain and biomass yield contribution by barley in the intercrop.

5. Discussions

5.1. Yield advantage in cereal-legume intercropping system

Annual intercropping have been reported more productive than their sole crop production (Zhu et al., 2016; Bedoussac et al., 2015; Qin et al., 2013; Hauggaard-Nielsen et al., 2001). This study also shows that pea-barley intercropping systems are over yielded in both grain and biomass dry matter production than their respective sole crops (table 2). Such over yielding were more prominent when soil fertility was low. In zero N fertilization, intercropping was 26% and 16% over yielded than barley sole crop and pea sole crop respectively. No significant influence of N fertilization was observed in total grain yield (table 3). Naudin et al. (2010) also obtained the comparable amount of grain yield in both unfertilized and N fertilized intercrops. This suggested that in organic farming or to resource poor farmers, cereal intercrop with legume is a viable alternative to increase the productivity. Besides, Higher N fertilization increased barley yield in both sole crop and intercrop and there was no strong influence on pea sole crops. In moderate N level (40 kg/ha) grain and total biomass yield in sole crop slightly increase but in higher N doses (80 kg/ha) the grain and biomass yield remained constant. But in intercrops, with the increment of N fertilization, the decrement of pea yield was much higher than the pea sole crop. This decrement is highly significant when pea proportion is low in intercrop. Such contrasting dynamic behavior was also observed in some previous studies (Bedoussac and Justes, 2010; Corre-Hellou et al., 2006, Hauggaard-Nielsen & Jensen, 2001; Jensen, 1996).

The benefits of intercropping is mostly measured by LER values. LER for grain yield showed that the environmental resources (such as light, nutrient and water) were up to 83% more efficiently utilized by intercrop than the sole crop when soil available N are low, but this efficiency were significantly decreased with the increment of N addition. There is a negative correlation of LER with mineral N availability during early vegetative stage and higher N accumulation by whole intercrop (Bedoussac and Justes, 2010; Rao and Willey, 1980). With the increment of mineral N level, total LER values decreases mainly due to the massive reduction of pea partial LER, while barley partial LER remain stable whatever N accumulation occurred by whole intercrop. Moreover total LER values also depends on percent of accumulated N derived from the atmospheric N_2 fixation by pea in intercrop. Reduced atmospheric N_2 fixation reduces the total LER while the partial LER not correlated with fixation (ibid). Increased N availability in the soil reduces the nodule establishment during the vegetative growth (Naudin et al., 2011) and subsequently reduces the atmospheric N_2 fixation by legume and reduces the pea plant growth affected by low competitive ability for light. Barley root density is much higher than pea. Thus the vegetative growth of barley take place earlier than that of pea crop (Andersen et al., 2005). Moreover due to deeper and faster rooting system at initial growth stage and high competitive ability for soil N acquisition in barley, at higher N level, its initial vegetative growth is much higher than that of pea in intercrops (Corre-Hellou et al., 2007). Jensen (1996) mentioned barley as up to 30 times more competitive than pea for soil N acquisition. Consequently higher competitive ability for light, barley growth increase rapidly but the shading condition subsequently decreased pea growth (Naudin et al., 2010; Corre-Hellou et al., 2006; Jensen, 1996). However this decrement of pea growth in intercrop decreases with the increasing the pea proportion and decreasing the barley proportion in the intercrop due to the increasing competitive ability of pea with barley, consequently total LER increased. It was also observed that in all growing seasons, the increasing the pea proportion in the intercropping increases total grain and biomass yield. This was due to the increasing amount of atmospheric N_2 fixation by pea crops, and higher complementarity and less competition between the component crops.

In all intercropping systems it was observed that barley growth was never affected by pea proportion. Even when barley was only 20 percent in the mixture it was not suppressed by pea crops which indicated that in cereal-legume intercropping system, higher proportion of legume helps both component crops for better growth and yield through complementarity for resources rather than interspecific competition. Thus Barley showed high degree of plasticity in terms of grain yield when barley proportion decrease 20, 50 and 80 percent in the mixture. In intercrop with reduced barley density, individual barley plant accounting for greater relative proportion of soil N accumulation than the individual barley in high density intercrop (Andersen et al., 2005). Hence the individual plant productivity increases and show greater yield plasticity in total production compared to the intercrop with high barley proportion.

In addition, intercropping seems to be considered as an effective way to better accumulation of existing soil N in the plants and reduces the environmental risk associated with the external N application. Indeed, in the field experiment result, in every following year total grain yield was higher than the previous year, perhaps it was happened due to the residual N effect from the previous cropping seasons (Adjei-Nsiah et al., 2008; Geijersstam & Mårtensson, 2006).

So when N is a limiting factor in the soil, higher proportion of legume in the intercrop is recommended for successful crop production. On the other hand, when farmers expecting higher proportion of legumes in the mixture and higher N input through symbiotic N_2 fixation in the agroecosystems, no N fertilizer is recommended to apply. But if the farmers expected higher production and higher cereal proportion in the total grain yield, a moderate N fertilization rate is likely recommended, nevertheless no significant outcome in total yield may be obtained.

5.2. Yield stability in different cropping systems and N effects

There is no strong experimental evidence of N fertilizer effect on yield stability. However some previous studies showed that high N fertilization brings higher variability in yield (Sileshi et al., 2012; Akinnifesi et al., 2006). Indeed, in my result, at 80 kg N level yield shows higher variability over the years than other N levels. However in 40 kg N level yield showed lowest variability, referred that N fertilization with moderate level likely increase yield stability rather than higher N fertilization. But the resources poor farmers whose cereal production is mostly depend on inherent soil fertility and faces the variability of yield year to year, intercropping of cereals with legume is a viable alternatives to improve the yield stability. Continuous use of inorganic N fertilizer reduces the soil organic matter and total soil N, consequently declining the yield (Bhandari et al., 2002). Where intercropping with legumes simultaneously provides both nitrogen and organic matter to the agroecosystems and more other ecosystem services, thus yields are less variable over the years. Indeed, in the regression analysis, intercropping systems showed higher yield stability compared to sole crops. Yield stability mostly depends on the response of cropping systems to the changing growing environment (Grover et al., 2009). Here both cereal and legume sole crop showed high respond to the N increment than intercrops. Moreover the regression analysis showed that higher pea proportion in the intercrop brought higher yield stability in the cropping system. Perhaps higher legume portion in intercrop helps to complementary utilization of environmental resources and higher N addition by symbiotic N_2 fixation.

Results for field experiment showed that, in most cases, CV for biomass yield is comparatively lower than the CV for grain yield for the respective cropping system. Such higher yield variability in grain is happened mainly due to disproportionate partitioning of total biomass into vegetative and reproductive structure over the years. There are several environmental reasons for such disproportionate partitioning of biomass including nitrogen availability in the soil, moisture availability, temperature, light etc. (Wu et al., 2013; Poorter et al., 2012). If the all other factors remain constant, then higher available nitrogen in the soil increase the plant biomass partitioning into grain (Cambui et al., 2011). Indeed, in this experiment, CV difference between grain and biomass of the intercropping systems is comparatively lower than that of barley sole crop CV difference, since pea added nitrogen to the soil through fixation.

5.3. Yield stability in higher yield level

Under adverse conditions yield stability may be more important to many farmers than high productivity under good conditions. However the meta-analysis for stability showed a negative relationship between mean grain yield and CV. That means stability in yield might only be achieved if the average yield level is high. Perhaps it is happens, because CV is the ratio of standard deviation to mean and for the equal standard deviation in two different yield level, CV is likely to be lower in higher average yield level compare to the lower average yield. This linear relationship is fully supported by Taylor's power law (TPL), which is generally used for several insect groups, earthworms, invertebrates and in many other ecosystems to describe an empirical relationship between the sample variance and the sample mean (Taylor, 1961). A recent study of Döring et al. (2015) on stability analysis in agronomy also got same relationship for CV and sample mean, although their different dataset showed both linear and non-linear relationship. One analysis performed by Chloupek et al. (2004) to measure the yield stability of some major crops grown in selected European countries from 1920 to 2000 and concluded that the crops with higher yield brought higher yield stability than the lower yielded crops and reduces the dependency on environmental condition of particular years. This results suggested that high yielding cultivar may have the ability to reduce the variability of yield over the years.

5.4. Yield variability in different climatic zone

Although only 17% experiments were from tropical climate, but intercropping is a very common practice in tropical region. In temperate region, where intercropping is mostly practice to produce animal feed and fodder but in tropical region farmers follow this practice for their food security and livelihood. The meta-analysis result revealed that yield in cereal monoculture production is highly unstable in tropical region. Today stability in food production is considering as an important factor for food security in this region (FAO, 2013). The important reasons for cereal monocrop yield variability in tropical region is the year to year climatic variation, high temperature imposed pest and disease incidence, and irregular rainfall.

Proper utilization of nutrients may occur if the plants is in physiologically good conditions, and if the soil hold enough moisture to dissolve the nutrients. Usually the efficiency of nutrient adsorption by plant is higher with average precipitation than the over precipitation and much higher than the dry seasons. Likewise, annual mean temperature also have impact on nutrient efficiency. In tropical regions, where temperature is high, the cereal crops have low nutrient efficiency than the subtropical and temperate regions (Chloupek et al., 2004). Besides, due to higher temperature, soil organic matter (SOM) content declining rapidly in the tropical region which also affecting the cereal yield stability. One study of Pan et al. (2009) on SOM and yield variability showed that for each 1% decrement of total SOM content, yield variability increase 10% over the years. This problem can be mitigate through carbon sequestration with intercropping (Wang et al., 2010; Peichl et al., 2006), since this sequestering carbon have implications on crop yields and long term yield stability (Pan et al., 2009).

Surprisingly the result showed that legume have higher yield stability than cereal sole crops in tropical region. Perhaps legumes have more adaptability in the higher temperature than the cereal crops. Indeed, the adaptability of crops is an important factor for yield stability and have a strong correlation with higher yield and yield stability. Higher the adaptability of a crops with the changing environment, higher the annual relative yield and yield stability would be obtain (Chloupek et al., 2004).

The meta-analysis result showed that both cereal and legume production is highly stable in sub-tropical region since the temperature and other environmental factors is favorable for grain production. But if the current trend of climate change is continue, food production in this region will also be hampered like tropical region due to high temperature and other climatic variability. However, comparing with subtropical and temperate climate, intercrop in tropical climate is highly profitable as it have significantly lower yield variability than both cereal and legume sole crop.

In meta-analysis result, cereal-legume intercrops grown in replacement design supports the hypothesis that lower relative density total (RDT) in replacement design reduces the yield variability in the intercrops better than additive design. One meta-analysis study by Iverson et al. (2014) indicate that intercropping in the replacement design significantly increase the yield and other ecosystem services than the additive design. In additive design there is high plant density induced higher interspecific and intraspecific competition. But in replacement design, addition of interspecific competition is replaced with the potential of reduced intraspecific competition. Thus in cereal-legume intercropping system when individuals of primary crop (cereal) are replaced with individuals of the secondary crop (legume), the per-plant yield of the cereal crop increase due to the lower intraspecific competition and proportionally higher nutrient uptake by individual plant (Andersen et al., 2005). Iverson et al. (2014) also mentioned that in additive designs, total intercrop yield didn't differ from the monoculture when the secondary crop was legume but total yield was significantly reduced when secondary crops was non-legume. By contrast, in replacement design, whether the secondary crops were legume or non-legume, total yield always increased from monoculture. In addition, legume price is higher than the cereal price. Even if anyhow the total yield in cereal-legume intercrop is lower than the cereal sole crop, still the total economic return is higher than the cereal sole crop due to the higher legume prices and less cost behind reduced fertilizers and pesticides. Overall intercropping in the replacement design have strong potential to provide win-win outcomes through increasing both yield and yield stability, consequently stable economic return.

5.5. Intercropping for food security and improved livelihood

The rapid increase of population and consequent pressure on food production are driving the agriculture towards greater intensification in most of the developing countries, particularly in Africa, where over half of the rural population lives below the poverty level (Ravallion et al., 2007; Sanginga et al., 2003). To date, greater yield losses can be accounted for extreme localized events like temperature variability and frequent drought in recent years, and limited access to external inputs by farmers than any other events (Sheffield et al. 2014; Akinnifesi et al., 2010). Consequently agricultural activities greatly reduced across these areas and substantially reduce the progress towards food security. It is well known that without adequate inputs, yields cannot be increased, but at the same time those external inputs either not available or not within the range of financial capacity of the most small scale or subsistence farmers. Many scientist have argued that current monoculture based modern agroecosystems has put global food production in greater peril and if any devastation in crop production happen, it will throw numerous people in food insecurity (Altieri et al., 2015; Altier and Nicholls, 2004). There are many examples of historical cases that monoculture threatened the global food production causes starvation of millions of people. The Irish potato famine due to wide spread cultivation of potato monoculture and the attack of late blight disease that causes 80% reduction of yield, resulting millions of people starved to death and more than 2 million people migrated to other countries. The great Bengal famine of 1943 in India and Bangladesh famine of 1974 due to a devastating disease that wiped out rice monoculture causes over 3 million of people's starvation death. To avoid such situation and to ensure the food security through increasing the yield level, current agricultural systems have to be resurgence on the basis of sustainable agriculture through increases on-farm crop diversity (Garrity et al., 2010). If such crop diversity through intercropping can be assembled properly in time and space, it can enhance the productivity of farming system over a wide range of environment and the more the crop diversity in the farming system, the more the resilience to the environmental perturbations could be obtained, thus ultimately ensuring food security (Frison et al., 2011; Gurr et al., 2003).

In Africa, the benefits of intercropping of cereals with legumes cannot be ignored. Although conventional monocropping system is much easier to large scale farmers who uses heavy machineries, synthetic fertilizer and pesticides, but the small scale farmers who don't have readily access to the market and grow different foods only to sustain themselves and their families, recognize that intercropping is the only way to ensure their food security and to maintain the livelihood. Currently Africa uses only 1 percent of the global fertilizers (Scialabba, 2007). In West Africa farmers uses only 8 kg/ha fertilizers annually compared with the other countries using 100-400 kg/ha annually (Singh & Ajeigbe, 2007). In Africa there are about 33 million small scale farmers, representing 80% of cultivated farm in this continent (Altieri et al., 2012). Over 85% of these small scale farmers have no access to the input markets due to lack of financial capacity. To these resource-poor farmers, intercropping cereals with legumes is the only source of nitrogen for successful cop production (Akinnifesi et al., 2010). Evidence shows that this intercropping system is over yielded despite lower or no application of external input. Intercropping of cassava as a staple crop is a common practice among the marginal farmers in Eastern Africa (Fermont et al., 2010). In Kenya and Uganda, around 51% and 30% respectively of cassava acreage were intercropped with mainly barley and also beans, sorghum, groundnut and cotton. By this way the economic return increase over 70% compared to the sole cassava production (ibid). Crop production in most of the western part of Africa still based on intercropping of cereals including maize, sorghum and pearl millet with cowpea. By following this intercropping system, farmers in Nigeria earned gross income over 300% more than the conventional monoculture, since their intercropping is over yielded and reduced expenses behind the fertilizers (Singh & Ajeigbe, 2007).

The Machobane farming system (MFS) in Lesotho is an example of fundamentally redesigned intercropping system producing multi-functional benefits (Dejene et al., 2011; IIRR, 1998). Climatic variability, reduced soil fertility due to top soil erosion, inadequate soil fertility management, land degradation, and low productivity of monoculture makes vulnerable the Lesotho's agriculture as well as threaten the food security and livelihood (Pretty, 1999). The Machobane farming system was developed in 1950s by Dr. James Machobane, a Mosotho agronomist, based on the experiment in his own farm for 13 years before disseminated it among the fellow farmers (Machobane and Robert, 2004). This farming system was designed to increase the productivity in the small scale farms in low mountain areas in Lesotho based on simple, low input intercropping technique and localized application of farm-yard manure and ash (from household waste), and incorporating potato as cash crop in intercropping. Due to the three times more productivity in MFS compared to the conventional monocropping system in Lesotho, it is considered that MFS practices in 0.4 ha (1 acre) of land is sufficient to ensure the food security of an average family of 5 members, where 1.2 ha of land required in conventional system (Mekbib et al., 2011). Intercropping in MFS practice consists of alternate rows of cereal or tuber crop with legume and vegetables. During April-May, farmers are planted wheat, pea and potatoes (the MFS cash-crops) as intercropping for harvesting them in following January-March and during summer season (August to October) they intercropped maize, beans, sorghum, groundnut and possibly pumpkins and water melons for harvesting them in November-December (Graves et al., 2004). Thus following this practice ensures food supply to the household all the year round. Crop residues are left in the field for nutrient cycling and the field is ploughed one in every five years. By incorporating pumpkin in intercropping, helps to reduce pest incidence, thus discourage the chemical pesticides application. Besides the higher yield, due to year round production MFS also decrease soil erosion, conserve soil moisture and suppress weeds. Crop diversity in MFS, makes it more drought resistance and this fields are green compared to the non-Machobane fields during drought periods (Pantanali, 1996). Between 2001 and 2005, when national yield was dramatically decreased due to severe drought, that time yield in low mountain areas followed MFS practice was quite high; maize yield was 14% high, sorghum yield 63%, bean yield 61% and potato yield was 294% high. Moreover, the farmers income fluctuation over the year have been substantially reduced due to low yield fluctuation of the individual crops, spreading the risk of fluctuation of yield and income among the diversified crops, and reduced dependency on external inputs like fertilizer and pesticides (Pretty, 1999). Finally, after reintroduced the MFS in 1991, until 2006 over 5,500 Mosotho farmers adopted this practices to improve their livelihood, moves the farming system towards sustainability in low mountain areas in Lesotho (Anonymous, 2015).

Like Africa, intercropping production of staple crops is much popular in Latin American tropic. More than 40% of cassava, 60% of the maize, and 80% of the beans in that region are grown in intercropping system (Francis, 1986). In this intercropping system, the productivity in terms of harvestable products per unit area is 20%-60% higher than the monocropping system. In Mexico, intercropping of maize, beans and squash in 1 ha of land produces as much food as obtained from 1.73 ha of monocrop (Gliessman, 1998). In addition, this maize-beans-squash intercrops produces more than 4 t/ha dry matter that goes back to the soil, compare with 2 t/ha dry matter in maize monocrop. Practicing of 'making *milpa*' (intercropping of maize with beans, squash and other useful herbs primarily for direct household consumption) is considering as the foundation of food security for many rural communities in Latin America. A study by Isakson (2009) in Guatemala showed that, 99% of the peasant considered this practice as the basic source of their family food security and livelihood.

One 4 years project in Bangladesh, India and Nepal was carried out to develop the livelihood of subsistence and small scale farmers, mainly focusing on intercropping of different crops in production system. The project outcome estimated that, in project area, intercropping system increases the farmers income 92% in Bangladesh, 83% in Nepal, and 74% in India compare to the income before the project period (Raseduzzaman et al., 2013). In china, one third of total cultivated land area is used for intercropping dominated multiple cropping and half of the total country production come from this multiple cropping (Zhang and Li, 2003). In Gansu province of northern China, farmers follow wheat-maize and wheat-soybean intercropping system, where wheat is 74% over yielded in wheat-maize intercrop and 53% over yielded in wheat-soybean intercrop than conventional wheat production (ibid). Such yield advantages are a true breakthrough for achieving food security and decent livelihood among the resource poor small-scale and subsistence farmers isolated from mainstream agricultural institutions.

Not only among the small scale farmers but also among the agro-pastoralist, intercrop is very popular. In arid or semi-arid region, most of the agro-pastoralist intercropping fodder crops with legumes to enhance forage quality and to produce more forage dry matter (Sadeghpour et al., 2013; Jones and Thornton, 2009). Legume incorporation significantly increases the protein concentration in animal feed resulting higher milk and meat production that accelerate the farmers' income.

Besides the annual intercropping, perennial intercropping is also a common practice in most of the tropical developing counties. This perennial intercropping also plays a significant role in development of smallholder's livelihood. For example, in Sri Lanka, rubber production is a traditional practice among the smallholders. Despite economically non-viable, farmers follow this practice to ensure govt. subsidy and to secure the land tenure where ownership is under dispute (Stirling et al., 2001). More than 60% of smallholder rubber growers are fully dependent on rubber production to maintain their livelihood and to meet daily living expenses. But this sole rubber production is not enough for their subsistence. Moreover during immature stage of the plantation farmers have no income from it, which can exist for six years or more. To overcome this problem, farmers intercropping banana in immature rubber garden to compensate the cash income. One long-term experimental study showed that, intercropping banana in rubber garden can improve the growth of both immature and mature rubber, resulting in earlier exploitation of latex (Rodrigo et al., 2001a). Thus rubber-banana intercropping have several advantages to the smallholder rubber growers: the improved growth of rubbers reduces the length of unproductive immature period that helps the farmers to get early income, while additional income is obtained from intercrop banana and increased latex yield. Rodrigo et al. (2001b) constructed a cash-flow for smallholder rubber growers and explicitly mentioned that over two-third of the households annual income derived from on-farm activities, of which 70% income are coming from intercropping in immature rubber garden.

In Papua New Guinea, since 1970, due to rapid population growth and migrants, per capita cultivable land of oil palm smallholders decreases dramatically and due to the shortage of cultivable land area it is difficult to maintain household food security and livelihood (Koczberski et al., 2012). From the beginning of 1990s decade, smallholder farmers stared intercropping immature oil palm with food crops such as sweet potato, taro, Yams, Cassava and banana, and ensure their year round income. Through this crop intensification, smallholders have reduced the requirement of per capita garden area from 0.06 to 0.04 ha (ibid).

It is well documented that climate change will have significant effect on both biotic and abiotic stresses in food production system and threatening the food security and livelihood sustainability. Crop diversification through intercropping can make the agricultural system more resilient to such biotic and abiotic stress (Newton et al., 2011). Over the last few decades, cereal production (such as maize and sorghum) in sub-Saharan Africa is severely constrained by several biotic factors including cereal stem borers and the parasitic weeds *striga* (Khan et al., 2008). Infestation of *striga* causes up to the 100% cereal yield losses in sub-Saharan region and total annual losses was estimated over US$1 billion that has a serious negative impact on food security and livelihood of over 100 million people (Kanampiu et al., 2002). This losses were more serious with the stem borer attack and reduced soil fertility. Such constraints could be effectively addressed with the novel technology of 'push-pull' method, based on locally available companion plants, where insect pest are repelled from the cereal crops and attracted by the 'trap crop' in the boarder (Khan et al., 2014, 2008; Cook et al., 2007). This method involves intercropping of cereals with forage legume, silverleaf desmodium (*Desmodium uncinatum*) and planting Napier grass (*Pennisetum purpureum*) as trap crop in the boarder. Volatiles emitted by the desmodium leaf repel the stemborer moth from the cereal field (push) and attracts by their natural enemies of Napier grass (pull). Desmodium also effectively suppressed and eliminates *striga* weed through allelochemical secretion by its root and improve the soil fertility by nitrogen fixation. In addition, both companion crops are used as high valued animal fodder, increase the milk production and diversifying the farmers' income. This intercropping technique reduces the stemborer infestation in maize up to 80% (Khan et al., 2000). It significantly increases the grain yield by at least 3 ton/ha without applying any pesticides (Khan et al., 2014). One evaluation of benefit cost ratio estimated that this intercropping technique have significant positive return on investment of over 220% compare to the monocrop by 80% and monocrop with pesticides used by 180%, makes the system economically propitious to the farmers (Khan et al., 2001).

Intercrop also more resilient to abiotic factors. For example, after Hurricane Mitch it was observed that in American hillsides, farmers following intercropping suffered less damage than their neighbors followed monoculture practice. After Hurricane Ike hit Cuba in 2008, one field survey was conducted to estimate the agricultural damage in the provinces of Holguin and Las Tunas, and found that the losses was only 50% in the field followed intercropping compare to 90% or 100% in monoculture fields (Altieri et al., 2012). Likewise, fields followed intercropping showed faster recovery (80-90% within 40 days) than neighboring monoculture fields.

Now-a-days stability in yield is been considering as an important attribute for food security (Schmidhuber et al., 2007; FAO, 2002). The stable yield over the growing seasons helps to ensure food security for small scale and subsistence farmers. Poor farmers who have no enough purchasing capacity and tried to meet their family demand through producing food in their limited land resources. If in any growing season yield level decreases, it will throw the whole family at risk of hunger. On the other hand, most of the small scale farmers have no enough storage facility. Even if the production is also high for the specific crops, it would force the farmers to sell their product in low prices, resulting gaining low economic benefit. Yield instability in the national level also significantly affected the farmers. Beyond the stable yield, in any year for a specific crop if yield level as well as total production increase sharply, then the market price drop down dramatically, resulting the farmers affected by economic losses. On the other hand, if yield level decreases, then the market price increase and sometimes reaches beyond the poor people's purchasing capacity and throw them in food insecurity. Both of the meta-analysis and yield experiment results of this study showed that monocropping cereal yield is highly variable than the intercropping system. Perhaps due to more stable yield in the intercropping systems, it is gaining interest among the small scale and subsistence farmers in the developing countries (Altieri, 2012).

Food security is not only the supply or produce enough food but also supply enough nutrition. The nutritional and environmental challenges are interconnected and to ensure food security both issues have to be addressed efficiently (Garnett, 2014). The current food system does not provide yet enough nutrition and calories to every people of the planet (Foresight, 2011; Lobell et al., 2011). Improvement of nutrition status can be achieved through the diversification of crop intensification in small-scale production. Today intercropping has been considered as an important mechanism to ensure the nutrition security in the developing countries. There are many traditional or indigenous vegetables that are characterized by high nutritional value compared to common vegetables like tomato, eggplant, cabbage etc. One home garden experiment in India showed that intercropping of different traditional vegetables in small home garden can provide much nutrition requirement for a small size family during whole year (Keatinge et al., 2011). Among the indigenous vegetables, moringa (*Moringa oleifera*) is highly nutritious and widely cultivated by indigenous people in most of the tropical region of Asia, Latin America and Africa. In most of the region, especially in Asia it is intercropped with a wide range of vegetables such as cluster bean, hot peeper, cowpea and onion (Ebert, 2014). The leaves and twigs are used as livestock feed and the fruits are used as human food. In Zimbabwe, most of the rural farmers intercrop sorghum with cowpea, pumpkins, cucumber and water melon with focusing on nutritional and livelihood benefits (Chivasa et al., 2000).

One study from South Africa showed that productivity of maize-bean intercropping was 15 to 26 percent more than conventional monocropping system (Mukhala et al., 1999). Overall nutrient content was higher in intercrop with respect to its maize monocrop. The energy content in intercrop was 11 to 18 percent and the total protein content was 60 percent higher than maize monocrop. Greater intercropped cereal protein concentration that in sole cropped wheat has also been reported by Bedoussac et al. (2015). Other nutrients like carbohydrate was 11 percent higher, vitamin C 100 percent, calcium more than 100 percent, as well as iron, magnesium, potassium and phosphorus was also higher in intercrop maize than maize monocrop. Thus intercrops have the ability to improve the protein and other nutrient accessibility in the malnourished children in the developing countries. Furthermore reduction of malnutrition among the children will ensure a better childhood life, resulting strong contribution in economic development during adult.

5.6. Future outlook

Despite the common practices of non-cereal-legume intercropping (such as maize-cassava intercropping) in African and Latin American tropics (Altieri et al., 2015), only one long term experiment on non-cereal-legume (legume-legume) intercropping was obtained from this region. Now-a-days cereal-cereal intercropping systems are gaining interest in some parts of China (Wang et al., 2015; Mu et al., 2013). The meta-analysis included only four experiments on cereal-cereal intercropping system that have been studied in china and proven advantageous. Indeed, the analysis showed that non-cereal-legume intercropping system are more stable compare to cereal-legume intercropping system. Additional long term studies on cereal-cereal intercropping system are needed, particularly from tropical region where climate is more variable, to determine whether its yield is stable or not. Such studies is very important because cereal is considering as the cornerstones for global food security. If cereal-cereal intercropping shows better land-use efficiency in terms of higher yield, and more yield stability than sole crops, it could keep greater contribution to the future global food security.

6. Conclusions

Now-a-days the benefits of intercropping is well recognized. The present study showed that intercropping system have significant positive effect on yield stability. In meta-analysis, cereal-legume intercropping system significantly reduces the yield variability of sole crops compare to non-cereal-legume intercropping system. Moreover intercropping in replacement design is deemed as advantageous, since it provides higher yield and higher yield stability compare to additive design due to reduced intra and interspecific competition and higher nutrient uptake by individuals. In tropical region, where cereal yield is highly unstable, there cereal-legume intercropping system significantly reduces the yield variability of cereal sole crop than that of other climatic zones.

The field experiment results showed that N fertilizer have no significant effect on intercrop grain yield, nevertheless a lower amount of N supply may slightly increase the yield. Moreover N fertilizer addition in soil significantly reduces the land-use efficiency of intercropping systems. Furthermore intercropping of cereals with legume seems to be a propitious cropping system as it provides relatively higher yield and more yield stability than the respective sole crops. In addition, by providing stable yield, intercropping system substantially reduces the fluctuation of farmers income over the years, even provides a more stable income throughout the year, which helps to improve their food security and livelihood. Moreover cereal-legume intercropping systems are more efficient and resilient to the changing climate, less input practice resulting less GHG emission, and have multifunctionality in agroecosystems.

Finally, according to the analysis, it can be concluded that cereal-legume intercropping systems following replacement design have significant effect on the reduction of the yield variability of cereal and legume sole crop production, particularly in tropical region where the monoculture yield is highly variable, and provides relatively higher yield than the monoculture production that boosting the farmers income as well as improve their food security and livelihood.

7. References

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